EXPERIMENTAL AND NUMERICAL STUDY OF THE ENHANCEMENT PARAMETERS ON A DOUBLE SLOPE SOLAR STILL PRODUCTIVITY

BY

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This thesis, written by **Faizan Ahmed** under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN AEROSPACE ENGINEERING**.

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Dedicated to

my beloved parents, brothers, and sister

ACKNOWLEDGEMENTS

"In the name of Allah, The Most Gracious and The Most Merciful"

All praise and thanks are to Almighty Allah, the creator of all worlds for providing me the courage and perseverance to complete this work sincerely. May there be every peace and blessings upon the holy prophet Muhammed (PBUH), his family and his companions.

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NOMENCLATURE

A	area (m^2)
C	specific heat capacity (J/kgK)
cc	height of the mirror (m)
F_{mg}	view factor
h	heat transfer coefficient (W/m^2K)
h_{fg}	latent heat of water (J/kg)
I	total solar radiation (W/m^2)
K_g	thermal conductivity of soil (W/mK)
L_{gw}	least width of the solar still (m)
M	molecular weight
m	mass (kg)
mi	mirror
$\dot{m}$	mass flow rate (kg/s)
n	day number in a year
P	partial pressure of water vapor (N/m^2)
Q	heat energy (W)

$\dot{Q}$ rate of heat energy transfer (W/s)

R ratio of beam radiation on tilted surface to that on horizontal surface

rr width of glass cover (m)

S_d distance from upper edge of mirror to outer edge of glass cover (m)

S_g shape factor for calculating heat loss to ground

T temperature (°C)

t time (s)

V wind speed (m/s)

Greek letters

α absorptivity

σ Stefan Boltzmann constant (5.67 x 10^{-8} W/m^2K^4)

τ transmissivity

ε emissivity

δ declination angle (degree)

ω hour angle (degree)

ϕ latitude (degree)

β glass tilt angle (degree)

ψ angle between mirror and glass cover (degree)

ρ_{gr} ground reflectivity

ρ density (kg/m^3)

ρ_m mirror reflectivity

Subscripts

a air

abs absorb

av average

b basin

bd blow down

c convection

d distillate

E east

e evaporation

fw	feed water
g	glass
gr	ground
l	leakage
m	mirror
N	north
r	radiation
ref	reflection
rm	reflected by the mirror
S	south
s	solar
T	total
W	west
w	water

THESIS ABSTRACT (ENGLISH)

NAME: FAIZAN AHMED

TITLE: EXPERIMENTAL AND NUMERICAL STUDY OF THE ENHANCEMENT PARAMETERS ON A DOUBLE SLOPE SOLAR STILL PRODUCTIVITY

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Clean water is important for our health and well being. The supply of drinking water is very limited in countries like Saudi Arabia which receive limited rainfall and the useable surface water is scarce. Hence, desalination is practiced in large amounts using non renewable energy sources such as oil/diesel and around 70% of the Kingdom's drinking water requirement is met by this process. Since the use of oil/diesel is a costly process and is also not environment-friendly, therefore there is a need to focus on renewable energy for water desalination as in this research.

In this research, an experimental investigation was carried out to examine the effect of critical parameters on the performance of a solar still. Outdoor experiments were carried out at latitude of 26° N in summer and winter seasons for Saudi Arabian climatic conditions. Various glass slope angles (25°, 30°, 35°, and 40°) and water depths (1 cm, 2 cm, and 3 cm) were tested. The best glass slope angle was found to be 35° while 1 cm water depth gave the best results for both the seasons. Since the productivity of a solar still is low in winter, an attempt is made to enhance the productivity of solar still by using external mirrors which reflect extra radiation onto the solar still. With the addition of external mirrors, the productivity was found to enhance by 82% in winter.

A mathematical model was also developed based on the thermodynamic and energy balance equations for the solar still. Simulations were carried out for all the cases to validate the experimental results. It was found that the experimental and numerical results were in good agreement with each other with an error of 5-10%.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

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THESIS ABSTRACT (ARABIC)

الاسم: : أحمد فايزان
العنوان: دراسة تجريبية وحسابية لمعاملات تعزيز إنتاجية تقطير المياه بالطاقة الشمسية
التخصص: هندسة الطيران و الفضاء
التاريخ: (1432هـ ، 2011 م)

الماء النظيف هام للصحة ، و مصادر مياه الشرب محدودة في دول المنطقة مثل المملكة العربية السعودية ، التي تشح فيها الأمطار والمياه السطحية الصالحة للاستعمال. ومن ثم فهي تعتمد على تحلية المياه بكميات كبيرة(حوالي 70 ٪ من احتياجات المملكة من المياه الصالحة للشرب مصدرها تحلية المياه) و المملكة العربية السعودية هي أكبر منتج في العالم للمياه المحلاة.وحيث أن ذلك مكلفاً كثيراً لذلك فإن استخدام الطاقة المتجددة

(الشمسية) في تحلية المياه سوف يكون حلاً جذاباً لقلة كلفته .

هذا البحث ، لدراسة تأثير المعاملات الحرجة لأداء الطاقة الشمسية لتقطير المياه. وأجريت التجارب في الهواء الطلق على خط عرض 26 درجة شمالا في مواسم الصيف والشتاء للظروف المناخية في المملكة العربية السعودية. تم اختبار العديد من زوايا أسطح الزجاج المنحدر (25 ° ، 30 ° ، 35 ° ، و 40°) ، وعدد من ارتفاعات (أعماق) الماء (1 سم ، 2 سم ، والطول 3). وقد تم العثور على أفضل منحدر للزجاج بزاوية 35 درجة و كان أفضل عمق للماء 1 سم ليعطي أفضل النتائج . وحيث أن الإنتاجية من الطاقة الشمسية منخفضة في فصل الشتاء ، فقد تم تعزيز الإنتاجية من الطاقة الشمسية باستخدام المرايا الخارجية التي تعكس إشعاعات إضافية للطاقة الشمسية. و مع إضافة المرايا الخارجية ، تم تعزيز الإنتاجية بنسبة 82 ٪ في فصل الشتاء.

كما تم إعداد نموذج حسابي على أساس معادلات توازن الحرارية والطاقة الشمسية. وقد أجريت المحاكاة في الاصل لجميع الحالات للتحقق من صحة النتائج التجريبية. وقد وجد أن النتائج التجريبية والحسابية كانت في اتفاق جيد مع وجود فروق من 5-10 ٪ فقط .

درجة الماجستير في العلوم
جامعة الملك فهد للبترول و المعادن
الظهران المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 Purpose of this study

This thesis is done to investigate the solar distillation process which is used to provide fresh drinking water in remote areas of Saudi Arabia having water scarcity problems. As a result, considerable attention is devoted to the development of a simple solar still which is locally fabricated and easily operable. Solar distillation is a process where energy such as solar radiation is used to distill pure water from saline water. Of the many methods used for water desalination, the current study focuses on solar distillation process as it provides a technically feasible and economically viable method of supplying drinking water in remote areas.

The purpose of this study is to contribute to the field of science and technology for solar distillation systems. These systems are designed for small families and communities who have access to sea water and face potable water scarcity problems.

1.2 Background

Many facets of life including food for eating, water for drinking, and transportation for moving depend on the availability of fresh water and energy. Growing population, industrialization, and urbanization are increasing the demand for fresh water in agricultural, industrial and domestic sectors. Inadequate fresh water supplies have long affected the rural communities and there is a significant struggle to meet the growing water demands. Moreover, there is a vast consumption of non renewable energy resources which lead to unsustainable way of life. These finite resources are being depleted while at the same time it is causing environmental damage, health problems, and an unknown global future due to climate change. A lot of hardships will certainly be faced in future if renewable energy sources are not utilized presently. Fortunately, renewable energy sources such as solar radiation and saline water supplies such as oceans are abundant in Saudi Arabia.

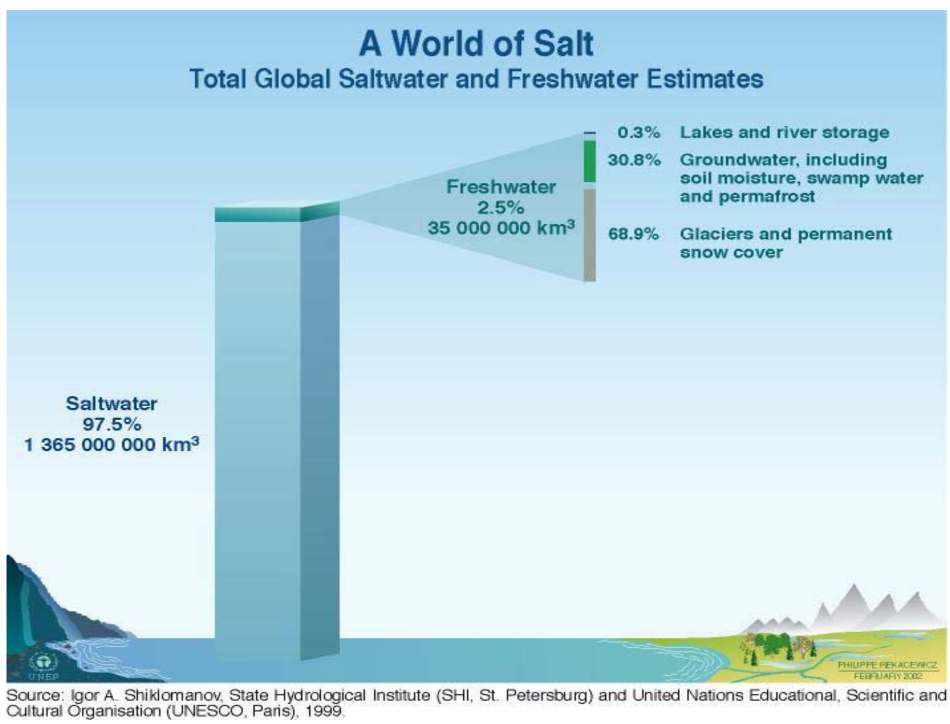

Figure 1.1 Water distribution on Earth

Only 2.5% of the water available on earth is fresh wherein only 1% is available for human use and the rest is ice [1]. US Census bureau statistics indicate that approximately

20% of the world's population lacks access to safe drinking water. This problem serves as a motivation to carry out the current research.

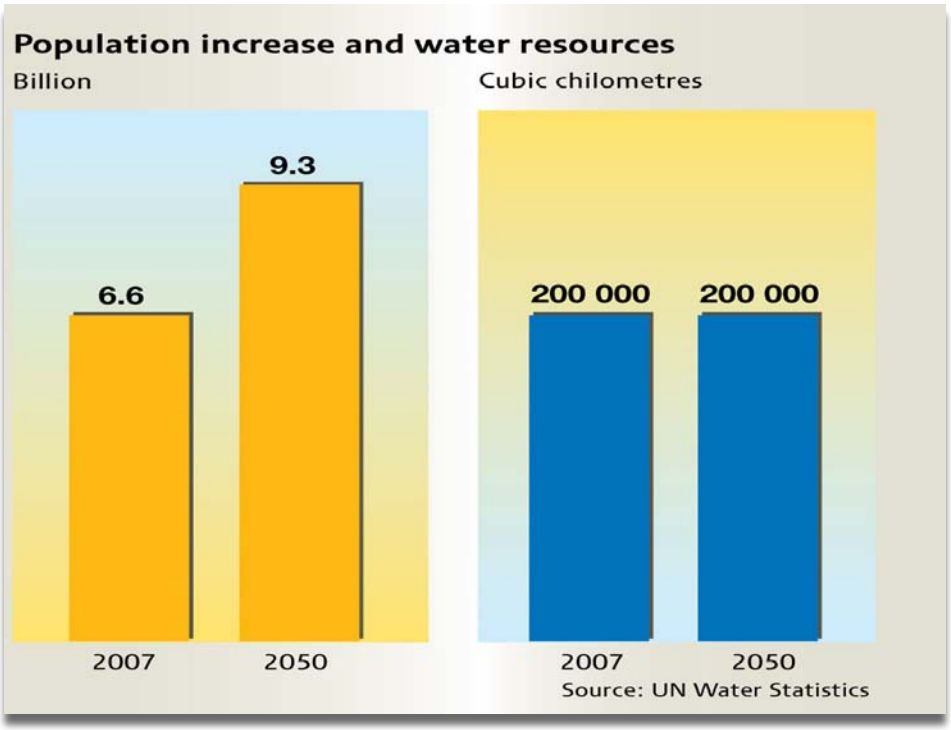

Figure 1.2 Statistics for population increase and water resources

According to the UN water statistics, the population will increase from the current 6.6 billion to 9.3 billion by the year 2050, while at the same time there is no increase in the water resources. Moreover, there is a high increase in water requirement for agricultural and industrial purposes.

With increase in population and pollution over the years, there is a considerable reduction in the amount of available fresh water. Almost one tenth of the global diseases can be prevented by increasing access to safe drinking water. According to the World Health

Organization (WHO), the permissible level of salinity in drinking water is 500 ppm whereas the sea water usually contains salinity in the range of 30,000 to 50,000 ppm. Consumption of sea water can lead to severe health problems such as dehydration. Table 1 shows the water salinity in parts per million for different water samples.

Table 1.1 Water salinity for different water samples [2]

S.No	Water Sample	Typical Salinity (ppm)
1	Fresh Water	1000
2	Brackish Water	7500
3	Saline Water	35,000
4	Brine	60,000

Availability of potable water is a major concern for the people living in the arid regions of the Middle East and the Gulf States due to the scarcity of fresh water resources. Desalination and water management are important steps in meeting the growing demands of clean and pure water. Water management strategies are also helpful in reducing the risks of water borne diseases.

1.3 Overview of desalination

Desalination is a process of converting sea water into potable water and it is the only method of increasing the fresh water supplies. But the problem with desalination is that it requires large amount of energy and hence most desalination systems rely solely on fossil fuels. Water desalination is practiced in many countries as can be seen in Fig 1.3.

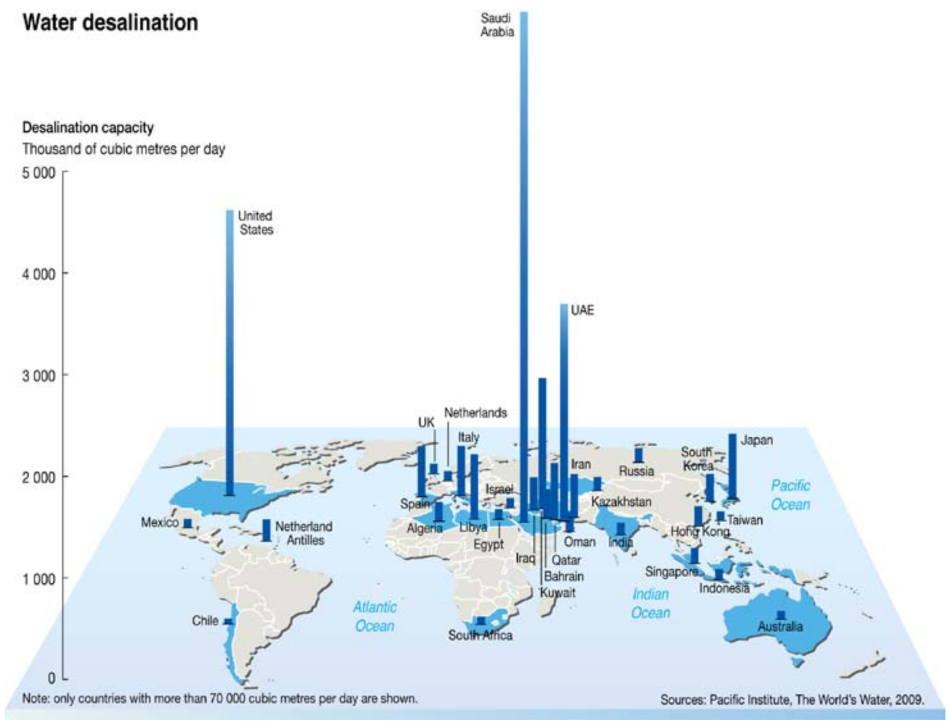

Figure 1.3 Desalination capacities for different countries

It has been estimated that for production of 1000 m^3/day of fresh water, 10,000 tons of oil is required per year [3]. Therefore, focus must be placed on the energy related problems. Hence it is important that the technological innovations such as desalination are researched, developed and implemented in a way that it makes the process of desalination economically viable and environmentally friendly.

Many methods have been developed to tackle the issue of drinking water scarcity. These methods which focus on obtaining pure water include adsorption, ion exchange, precipitation, electrolysis, and donnan dialysis. Among these methods, adsorption and precipitation are the most common in use. In the precipitation method, chemicals such as lime [$Ca(OH)_2$], dolomite (magnesium salts), and alum [$Al_2(SO4)_3$] have been widely used. The precipitation method is quite simple and economical but there is sludge disposal problem associated with it. Adsorbents such as alumina, fly ash, and carbon are used to adsorb fluoride from waste water. However, the drawback with adsorption process is that the adsorption capabilities decrease sharply under saline conditions.

Desalination technologies are classified based on the ways in which they separate salts from the saline or brackish water. These methods include:

1. Phase change separation (e.g. distillation)
2. Membrane separation (e.g. reverse osmosis, electro-dialysis)

Based on the particular application, any of the above two methods can be used for purifying brackish or sea water. Membrane separation processes can be divided into reverse osmosis and electro-dialysis.

In reverse osmosis process, water is forced through a semi-permeable membrane by applying strong pressure, thereby allowing only fine water molecules to pass through it. Many contaminants such as heavy metal and chemical poisons are removed by this process. Fig 1.4 shows a pictorial view of this process.

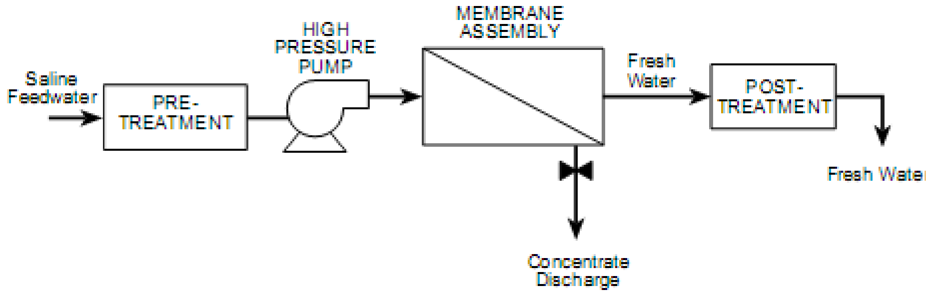

Figure 1.4 Reverse osmosis process [4]

The process of electro-dialysis uses a current source to maintain oppositely charged electrodes placed outside a pair of membranes which allow only the passage of anions or cat ions through the central water passage.

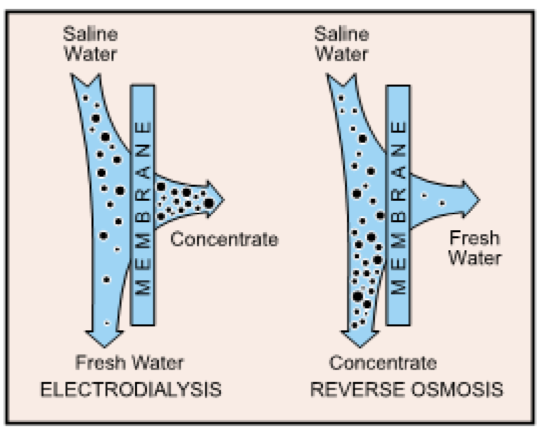

Figure 1.5 Comparison of electro dialysis and reverse osmosis processes [4]

After the ions are removed from the water, only desalinated water remains. A comparison between the above two processes can be seen in Fig 1.5.

1.4 Distillation

Although all the above stated methods are effective for water purification, they are expensive and hence not affordable to people with low standard of living. Hence there is a need for a simple, low cost, efficient and long lasting technology which can meet the requirements of a common man.

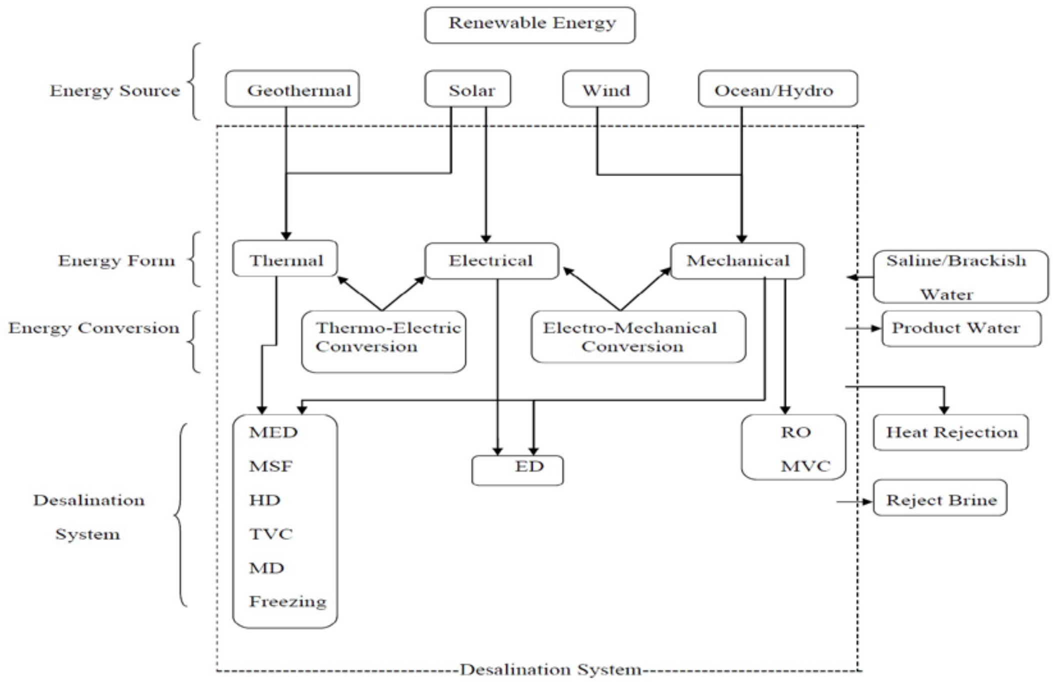

Figure 1.6 Renewable energy processes used for desalination

Distillation is one of the simplest methods that can be used to purify brackish or saline water. In this process of distillation, brackish water is evaporated using a heat source and the vapor is condensed to obtained pure water. Renewable energy resources provide continuous source of energy which is waiting to be tapped and offers great promise which requires significant investment in research, development and implementation.

The utilization of renewable energy depends on various parameters like location, season, time of the day, and climatic conditions but the only concern with renewable energy is its storage, conversion and transmission. Since solar radiation intensity is very high in Saudi Arabia, very high importance is given to the utilization of solar energy for obtaining pure water.

With the recent advancements in the usage of solar energy, solar distillation could be a very economical and highly productive process. This process is used to provide fresh drinking water in locations where the quality of water is poor, fresh water supply is inadequate, or treatment options are not available. The obvious advantage of solar distillation is that energy required for conversion is free and its technology is very simple.

Solar stills are one of the solar devices which can be used for fresh water production and is considered as the cheapest solution for purifying saline/brackish water due to their low cost and ease of maintenance. Hence solar stills have gained huge importance and high quality research is being done globally to study the performance of a solar still under different criteria's.

Solar stills can be used effectively in places where the fresh water demand is less than 200 m^3/day [5]. Stills can be classified into active and passive categories. An active solar still is provided with additional heating source such as solar collectors or heaters. A passive solar still does not require any additional heating source which means that the heat collection and distillation takes place in the same system. Many solar stills have been built with innovative ideas in order to increase the production rate.

Some of them are:

1. Wick still

This solar still is provided with a wick such that one end is in the feed tank and the other is inside the still. Water is fed into the still by capillary action of the wick because of which there is only a thin layer of water inside the tank which leads to higher water temperature and production rate.

2. Multiple-effect basin still

This type of still consists of more than one basin placed on top of each other. The latent heat of condensation in one basin is utilized in heating the basin above it.

3. Hybrid still

These are unconventional solar stills which incorporates the use of external attachments to the still in order to enhance the distillation process. These stills can also be used for other purposes such as:

a. Rain water collection: A trough is attached externally to the still for collection of rain water which can be later used as feed for the still.
b. Greenhouse heating: A solar still is installed on top of the greenhouse with its roof serving as the cover of the still.

Many solar stills have been developed in the past and the focus has always been on the ways to improve the efficiency of the still. Some sophisticated solar stills have also been constructed earlier, but the benefit of increasing the productivity is not substantial because of the complexity of the unit. Hence a lot of emphasis is placed on designing a solar still without much complexity and then finding ways to enhance its productivity.

1.5 Objectives

The main drawback of a traditional solar still was the low amount of distilled water produced per unit area which makes the solar still unacceptable in some instances. Therefore, there is a great scope to improve the efficiency of such type of solar stills and one such attempt is made in this study.

1.5.1 Experimental analysis

The first objective of this research is to conduct outdoor experiments to study the effect of design, operational and enhancement parameters on the productivity of solar still. These parameters are listed below.

1. Cover Slope Angle
2. Water Depth
3. Addition of External Mirrors

The design and operational parameters which include cover slope angle and water depth respectively are to be tested for summer and winter seasons in Saudi Arabian climatic conditions at latitude of 26° N. After optimizing these two parameters, an attempt is made to enhance the productivity of solar still by using external mirrors. Since the productivity of a solar still is relatively low in winter, the effect of using external mirrors is more significant in winter. Hence, a winter study was done with external mirrors.

1.5.2 Numerical analysis

The second objective of this research is to carry out a numerical analysis in order to validate the experimental results. This numerical analysis involves thermodynamic modeling of solar still using various mass and energy balance equations consisting of the design, operational and enhancement parameters mentioned above.

CHAPTER 2

LITERATURE REVIEW

Many extensive studies have been carried out in the past focusing on the solar distillation process. A comparison between different solar energy systems for various applications was done by Mamlook et al. [6] using fuzzy set methodology. The systems which they took into consideration were solar distillation, solar water heating, solar space heating and ventilation, solar water pumping, photovoltaic and solar electric power production. The comparison was based on benefit to cost ratio. Their results showed that solar distillation is the best choice and should be given the highest priority in terms of research and development. Hence a lot of focus is placed on solar stills which are used for water distillation.

A solar still is a device used for purifying saline/brackish water. It consists of a base tank (basin) and a transparent top cover made of plastic or glass. The sun's heat evaporates the water in the basin leaving behind the salt and other impurities. The vapor from the evaporated water condenses on the top cover and trickles down the surface into an outlet channel provided for water collection. Fig 2.1 shows the schematic diagram of a solar still.

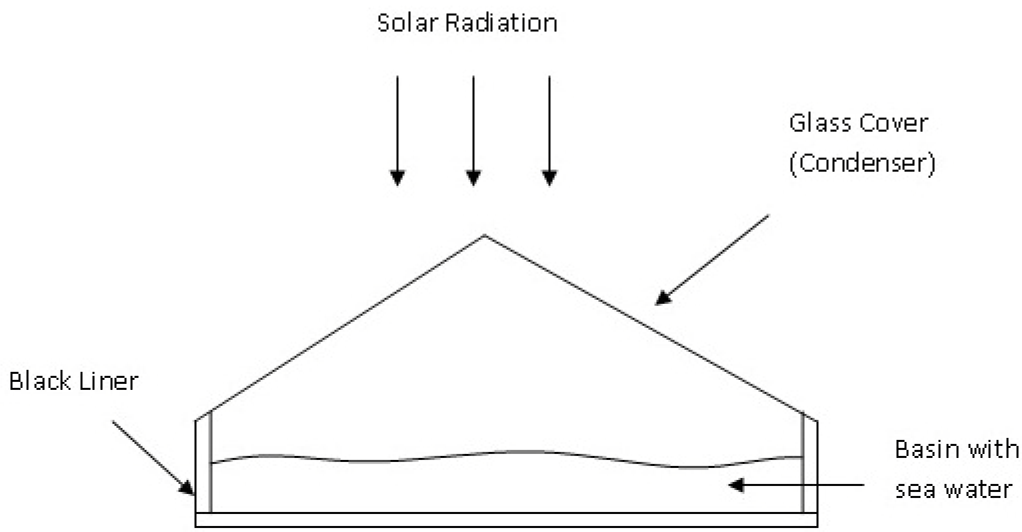

Figure 2.1 Main components of a solar still

The parameters affecting the performance of a solar still that are of prime importance to the researchers include:

(1) Cover slope angle

(2) Water depth

(3) Ambient temperature

(4) Wind velocity

(5) Solar radiation

In this regard, several experimental and numerical investigations dealing with various aspects of solar stills have been carried out.

2.1 Cover slope angle

Glass tilt angle and water depth are important parameters that directly affect the productivity of solar still. Singh et al. [7] carried out a numerical analysis (for latitudes of

13–28° N) considering the effect of solar intensity, wind velocity, water depth, and cover tilt angle on the productivity. They indicated that the optimum glass tilt angle for maximum annual yield should be the latitude of the location. Kumar et al. [8] did a similar study in India (latitude 28.36° N) by using analytical expressions for water and glass temperatures and based on their numerical analysis, the annual performance of an active solar still is optimum when the glass tilt angle is 15°.

To study the effect of design parameters, Kamal [9] did an experimental and theoretical analysis on the basin type solar still for the spring climatic conditions of Doha (Qatar) at latitude 25.3° N. He recommended a cover tilt angle of 10° for summer and 15° for winter to obtain high quantity of distilled water. In a similar study, Enein et al. [10] reported that the cover tilt angle should be as low as possible in summer and 50° in winter for Egyptian conditions (latitude 30.48° N). While studying the annual performance of solar still, experiments were conducted by Nafey et al. [11] (latitude 31.17° N) using various glass tilt angles and they found a similar trend in the results as obtained by Enein et al. [10]. A thermal analysis using internal heat and mass transfer relation was done by Tiwari et al. [12] in order to optimize the glass cover inclination for maximum yield in Indian conditions (latitude 28.36° N). Their results are also in agreement with those obtained by Enein et al. [10] and Nafey et al. [11]. Mathematical modeling was done by Hinai et al. [13] to predict the annual performance of solar still in Omani climatic conditions (latitude 23.36° N). Their numerical results also show that the productivity increases with decrease in glass tilt angle in summer and in winter the converse is true.

An experimental and numerical analysis was done by Dev et al. [14] to study the effect of cover tilt angle for summer and winter seasons in Indian conditions (latitude 28.36° N) Tests were conducted in April, June and November and they concluded that the optimum inclination angle for best performance of a solar still is 45° for both the seasons. Though the study done by Dev et al. [14] is at different latitude when compared to the above mentioned works, it is in contrast to the results obtained by other researchers [10, 11, 12-13]. Akash et al. [15] conducted experiments in Jordan (latitude 31.57° N) by varying the glass tilt angles and they found that 35° glass inclination angle gives the maximum yield in the month of May. While investigating different parameters affecting the productivity of a solar still, Elkader [16] obtained similar results at latitude 31.17° N with 35° glass slope angle giving the maximum yield. It was found that there was an increase in productivity by 19.5 % and 66.6 % for two different models having 30° glass slope angle and varying base slope angles.

2.2 Water depth

Sahoo et al. [17] conducted experiments using various test matrixes to find out the hourly output and total productivity of the single slope solar still. Their test matrixes included variations in the volume of water in the base tank and modifications in the design by using blackened surface and thermocol insulation. Upon changing the volume of water in the base tank, they found that the productivity increased by 11% when capacity of water was raised from 10 liters to 20 liters, hence changing the level of water in the base tank. With this volume of water, they modified the design by using blackened base liner and the efficiency increased by 4.69%. To further improve the efficiency, they added thermocol insulation to the above setup and found the productivity to improve by 6.05%.

Several researchers [8, 9, 11, 13-15] studied the effect of water depth and their results indicated that the productivity decreases in a linear relation with increase in water depth. Efforts have also been made by Kamal [9] and Hinai et al. [13] to find the optimum value of water depth.

Although a lot of research work has been done on the effect of glass tilt angle in different countries, there is a need to study the various parameters involved in it. This can be observed by the results that have been found in the literature [7], [9], [10], [14]. Therefore, in the present study, an effort is made to optimize the glass tilt angle for maximum seasonal output in Saudi Arabian climatic conditions.

2.3 External mirrors

Various design modifications were made to improve the performance of the solar still. Abdallah et al. [18] suggested the installation of internal reflecting mirrors in single slope solar still which gave an average of 30% increase in productivity. Fig. 2.2 shows the schematic diagram of solar still with internal reflecting mirrors. They modified the still design from flat basin to step wise basin and found that the efficiency increased by an average of 180%. There was a further improvement in production rate when the step wise basin was coupled with a sun tracking system which resulted in an increase of about 380%.

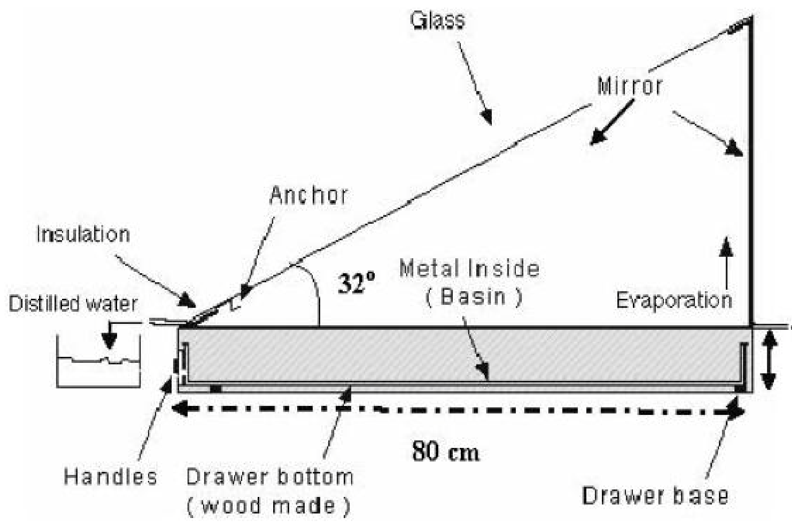

Figure 2.2 Solar still with internal reflecting mirror [18]

A theoretical analysis of basin type solar still with fixed internal and external reflectors was done by Tanaka et al. [19]. Fig. 2.3 shows a schematic diagram of the solar still with internal and external reflectors. A geometrical method was proposed to calculate the solar radiation reflected by the internal and external reflectors. They found that these reflectors were less effective in summer and reported that there was an increase in the productivity significantly throughout the year with an average of 48%.

In a similar study, Tanaka [20], [21] studied the effect of inclination of the external reflector in summer and winter seasons and found that productivity can be increased in summer season by inclining the reflector. A schematic representation of the still with inclined reflector is shown in Fig. 2.4. However, the results for the winter season showed greater increase in productivity with inclined reflector. When compared with the still without the reflectors, he found that the productivity of the still with inclined reflector is 2.3 times higher in winter.

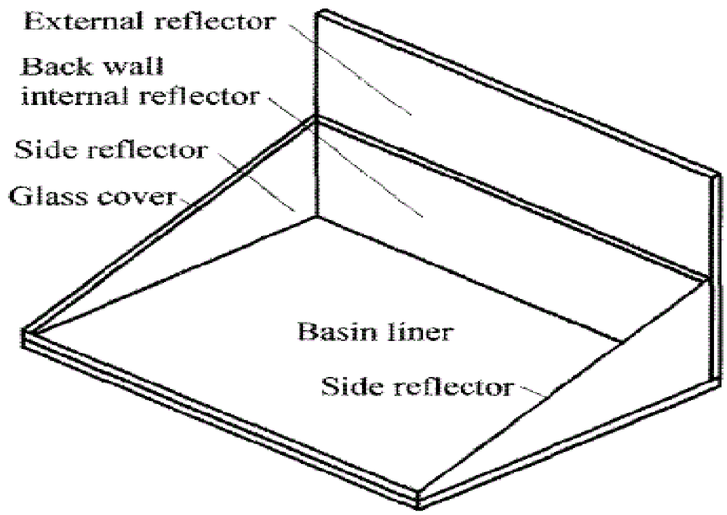

Figure 2.3 Solar still with internal and external reflectors [19]

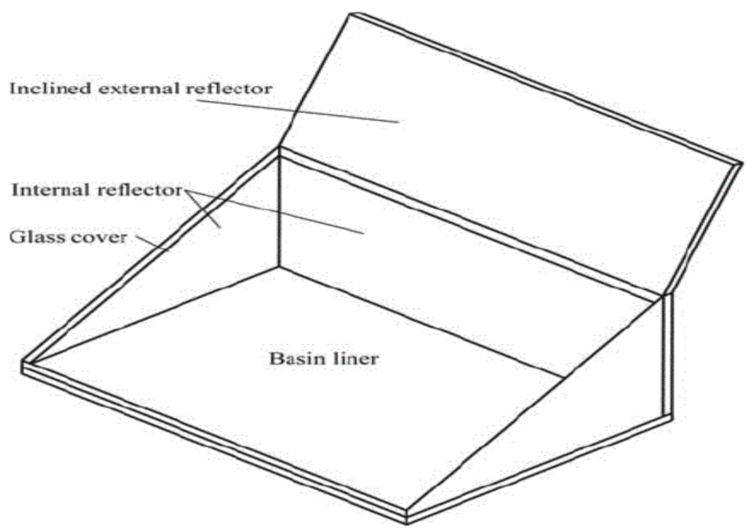

Figure 2.4 Solar still with inclined external reflector [20]

Tamimi [22] investigated a single basin solar still with inner mirrors and found that the use of inner mirrors enhances the productivity significantly. The rapid spoiling of the inner mirrors was identified as a disadvantage in using mirrors inside the solar still [23].

Therefore, Sebaii [23] used external mirrors in his study on the performance of a double slope solar still. Two mirrors were tilted at an angle and fixed to the outer side of the solar still as shown in Fig. 2.5. It was reported that the radiation falling on the solar still is increased significantly with the use of these external mirrors.

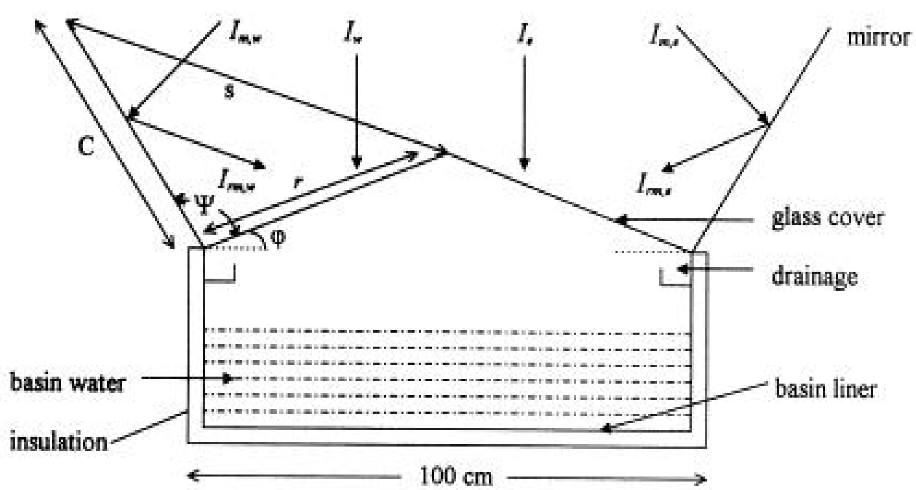

Figure 2.5 Solar still with external reflectors [23]

Since very little experimental work has been found in literature supporting the effect of reflectors, a study needs to be done which incorporates the use of external mirrors to reflect extra radiation on the still. Moreover, using rotatable mirrors which can be adjusted throughout the day with the movement of the sun can help in reflecting maximum radiation at all times.

2.4 Other enhancement methods

Of the many other methods used for enhancing the productivity of solar still, few are presented in the following section.

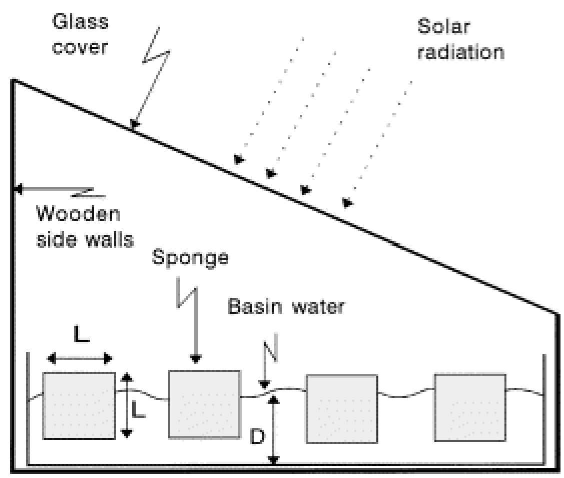

Figure 2.6 Solar still with sponge cubes [24]

Abu-Hijleh et al. [24] carried out an experimental study of single slope solar still which was focused on placing sponge cubes in the basin water to enhance the productivity. They found that there was a significant increase in water production in the range of 18% to 273% when compared with a reference still without sponge cubes. Various combinations of sponge cubes as seen in Fig. 2.6 were tried and the optimum combination was reported as sponge cubes with 6cm sides, 20% sponge to basin water volume ratio and 7 cm basin water depth.

An experimental investigation of single slope solar still was made by Rajvanshi [25] to study the effect of adding dyes such as black napthylamine, red carmoisine, and dark green. He found that the dye solution enhances the still productivity by 29%. Black napthylamine was found to be the best dye in his study.

Badran [26] studied the effect of using different enhancers such as asphalt and sprinkler in single solar slope still. The results showed a significant increase (29%) in still productivity when asphalt was used. The sprinkler combined with asphalt, resulted an increase in the output by another 22%. He also studied the effect of water depth on solar still productivity and concluded that the efficiency decreases with increase in the water depth.

Nafey et al. [27] conducted experiments to enhance the productivity by using black rubber or black gravel materials in the base tank of a single slope solar still. They studied the effect of different parameters such as rubber thickness and gravel size under the same conditions. Their results showed that black rubber (10 mm thick) increases the efficiency by 20 % at the conditions of 60 l/m^2 brine volume and 15° glass cover angle. The use of black gravel (20-30 mm size) increased the production rate by 19% at conditions of 20 l/m^2 brine volume and 15° glass cover angle.

Karaghouli et al. [28] conducted experiments with fabricated single basin and double basin solar stills as seen in Figs. 2.7 and 2.8. The glass slope angle for the single basin still was kept 36° with horizontal while for double basin still it was 12° with the horizontal.

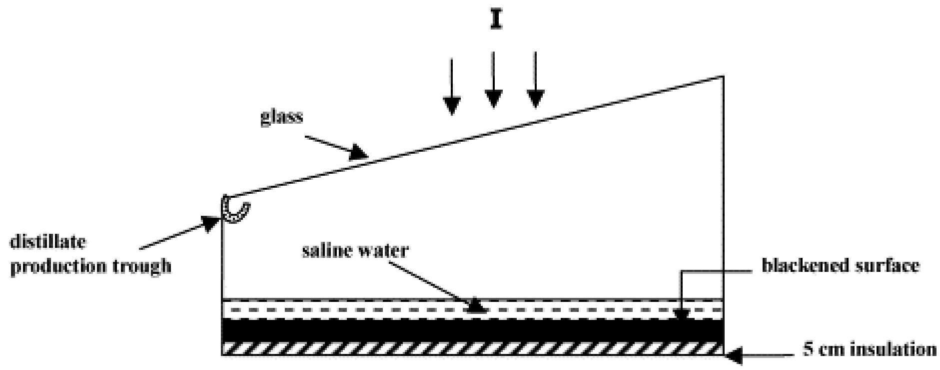

Figure 2.7 Single basin solar still [28]

They found that the efficiency of double basin still was 8% higher than that of single basin still. Upon insulating the above stills with styrobore insulating material, they found that they efficiency of double basin increased by 13% with respect to the single basin solar still.

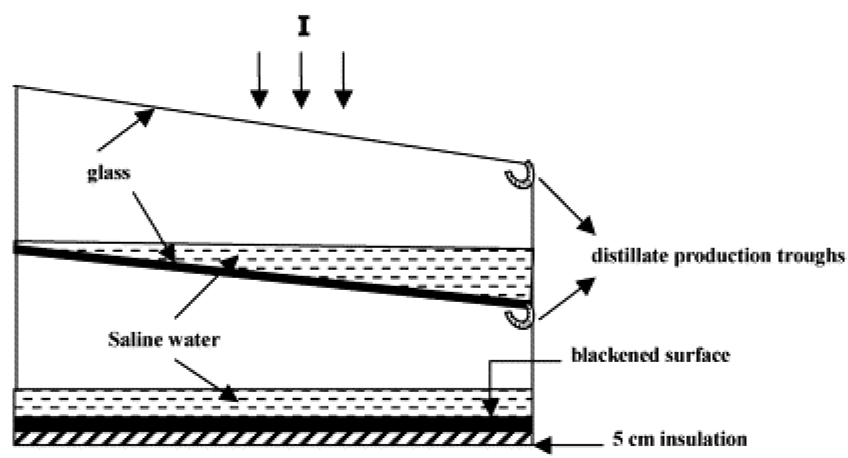

Figure 2.8 Double basin solar still [28]

In their effort to enhance the productivity, Akash et al. [29] studied the effect of using different absorbing materials on a double slope solar still. Their experimental results showed that an absorbing black rubber mat increases the productivity by 38%, while black ink increased the efficiency by 45%. They found that black dye mixed in saline water was the best absorbing material which gave an efficiency increase of 60%.

After reviewing the above literature wherein several attempts were made by different researchers to enhance the productivity of solar still, it is felt worthy to investigate the effect of glass tilt angle and water depth on the productivity of solar still. Experimental enhancement of a double slope solar still also needs to be done using the technique mentioned in the first chapter. Mathematical modeling of the solar still will help to validate the experimental results with the numerical computations. The present study is partial implementation of the two patents [30] and [31] in this field of solar distillation.

CHAPTER 3

EXPERIMENTAL WORK

The experimental part of our study deals with the design, fabrication and testing of a double slope solar still with the technical specifications as given below.

3.1 Design of double slope solar still

The main components of a solar still are base tank and top glass covers. Four units of double slope solar still were designed by varying the glass cover slope angle. The dimensions of each unit are specified below. Fig 3.1 shows the isometric view of a double slope solar still.

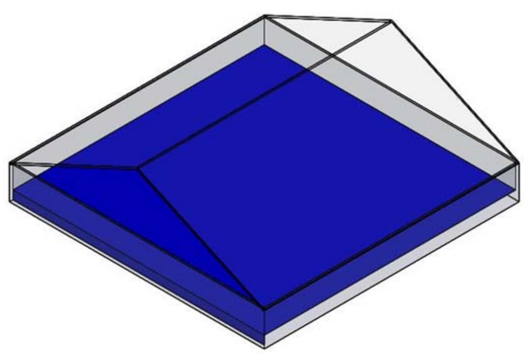

Figure 3.1 Isometric view of double slope solar still

Table 3.1 Design parameters of double slope solar still

S.No	Component	Solar Still	Dimension		
			Length (m)	**Breadth (m)**	**Height (m)**
1	Base tank	*Slope Angle 25°*	1	1	0.06
		Slope Angle 30°	1	1	0.06
		Slope Angle 35°	1	1	0.06
		Slope Angle 40°	1	1	0.06
			Length (m)	**Breadth (m)**	
2	Top glass covers (rectangular)	*Slope Angle 25°*	1	0.55	
		Slope Angle 30°	1	0.57	
		Slope Angle 35°	1	0.61	
		Slope Angle 40°	1	0.65	
			Side 1 (m)	**Side 2 (m)**	**Side 3 (m)**
3	Side glass covers (triangular)	*Slope Angle 25°*	1	0.55	0.55
		Slope Angle 30°	1	0.57	0.57
		Slope Angle 35°	1	0.61	0.61
		Slope Angle 40°	1	0.65	0.65

3.2 Fabrication of double slope solar still

All the four stills were built at KFUPM. The various components of the still were selected from locally available materials. The materials which were used for the fabrication of solar still are given below along with the additional attachments used in various stages of the experimental study.

1. Galvanized Iron (G.I) Steel tank
2. Black Paint
3. Window Glass
4. Silicon Rubber and Aluminum Strips
5. Water Pipes, Bottles and Tables
6. Mirrors

Galvanized Iron of 3 mm thickness was used for manufacturing the tank base since it has good formability. Two holes are provided in the base tank of each unit so that the distilled water can be collected in a measurable bottle kept beneath the still. A layer of black paint was applied on the inner and outer sides of the base tank so as to improve the absorptivity of the tank.

Figure 3.2 Base tank with a layer of black paint

Flexible plastic pipes were used to allow the flow of the distilled water from the still into the measurable water bottles. Two pipes were fixed diagonally in each still. Measurable water bottles were kept beneath the still and are connected to the flexible pipes so that the distilled water is collected in these bottles. Four wooden tables having a height of 2 feet were manufactured and the stills were placed on them.

Window glass of 6 mm thickness was used to cover the base tank from the top. A small hole is provided in one of the side glass covers for feeding sea water into the still. The glass cover of the still is adjusted on the edge of the base tank and is then sealed. Silicon rubber was used to seal the glass covers and the base tank since silicon has good bonding between glass and many other materials. L shaped aluminum strips were fixed on all the edges of glass and base tank to provide solidity to the solar still.

Figure 3.3 Glass pieces assembled with silicon rubber and Aluminum strips

Figure 3.4 Double slope solar still with glass covers and base tank fixed together

Figure 3.5 Fabricated double slope solar stills with cover slope angles: 25°, 30°, 35°and 40°

A digital thermometer was used to measure the temperature of glass and water in the basin. The ambient temperature was also recorded. The amount of distilled water was measured using the measurable bottles. The sea water used in our study was collected from King Fahd University of Petroleum & Minerals (KFUPM) beach, Khobar, Saudi Arabia. This water has 3.5% salinity. Four wooden clamping stands were manufactured so that the external mirrors could be fixed into it. Mirrors were fixed in the wooden clamping stands which were then kept around the stills to increase the incident solar radiation falling onto the stills.

3.3 Solar still operation

The principle of operation of a solar still is quite simple and similar to the rainfall phenomena. Sea water is fed into the base tank which is covered on the top using transparent inclined glass. The solar radiation is transmitted through the glass covers and is absorbed by the basin liner which heats up the saline water. As the saline water heats up, the air inside the still gets saturated and it starts condensing on the glass covers which are cooled by convection due to the effect of ambient wind. The condensed water flows through the distillate channel into the water collection bottles kept outside the still.

3.4 Performance measurement of double slope solar still

The four water distillation units designed and fabricated were tested to examine the effect of various operating parameters under the same weather conditions. The still was placed in South-North orientation. The experiments were carried out from sunrise to sunset while making hourly recordings for the distillate water and the temperatures of glass and water in the basin. The ambient temperature, wind speed and direction were also noted every hour. The experiments were conducted in an open ground on KFUPM campus, at Dhahran (latitude 26° N), a city in the Eastern Province of Saudi Arabia. The experiments were carried out during summer (June, July 2009) and winter seasons (December 2009, January 2010).

Feed water is supplied into the base tank through the inlet provided. A constant water level is maintained inside the base tank by monitoring its level every hour. It was ensured that the still is sealed properly to avoid heat loss. Few preliminary tests were conducted to ensure proper functioning of the still. There was a periodic maintenance of these still after every 6 days of still operation. This maintenance included cleaning the inner surface of base tank where there is a lot of salt accumulation, applying black paint, cleaning the glass surfaces from dust so as to improve its absorptivity, checking the water delivery pipes for water leakage near the joints, and visual inspection of the glass and base tank sealing to detect air gaps through which there can be heat losses. The different modes of operation of the still are discussed below.

3.4.1 Cover slope angle

The solar stills with cover slope angles of 25°, 30°, 35° and 40° were examined to study the effect of their variation on the productivity. These angles were selected based on the previous works [9, 13, 15] done in other GCC countries.

Figure 3.6 Solar stills with various cover slope angles

The base tank is filled with sea water to a height of 1 cm and is checked every hour to maintain its level. With the passage of time during the day, the solar radiation increases and amount of distilled water collected also increases. The distilled water from each still is measured on an hourly basis and the total quantity of water collected in a day is calculated. The best cover slope angle was found based on the experimental results obtained from each still. The temperature measurements for glass and basin water were done hourly for all the stills. The experiment was repeated for four days to check for consistency.

3.4.2 Water depth

Next, the four stills with the above cover slope angles were tested for the effect of water depth on the productivity of the still. The different water depths tested were 1 cm, 2 cm and 3 cm. These water depths have been chosen due to the ease of operation of the still with these depths. All the stills are filled with 1 cm water depth on first day, 2 cm water depth on second day and 3 cm water depth on third day. The best water depth is found based on the experimental results obtained from each still. These water depths were tested on a set of three successive days. The experiment was repeated for two more sets to check for consistency.

After studying the combined effect of cover slope angle and water depth on the productivity of the solar still, the best cover slope angle and best water depth was found out.

Figure 3.7 Condensation on the top glass covers of solar still

3.4.3 External mirrors

In order to enhance the productivity of the solar still, this mode of operation involves the use of external mirrors to increase the amount of solar radiation incident on the still. Four mirrors fixed on wooden stands were used to surround the still. These mirrors were placed at a distance of 1 m from the still and were tilted at an angle of 65° from the glass cover of the solar still. These wooden stands were built to withstand heavy winds, dust storm, and rain. The still with the best values of cover slope angle and water depth was chosen for this mode of operation. Feed water was filled in the base tank and the experiment was carried out in the same manner as discussed above. The experiment was then repeated the next day without the mirrors. A comparison was done for these set of days in order to know the increase in productivity. The experiment was repeated for another two sets to check for consistency.

Figure 3.8 Operation of solar still with external mirrors

Figure 3.9 Photograph of accumulated salt in the base tank after water distillation

3.5 Work plan

The above experimental work can be summarized in the chart as shown below.

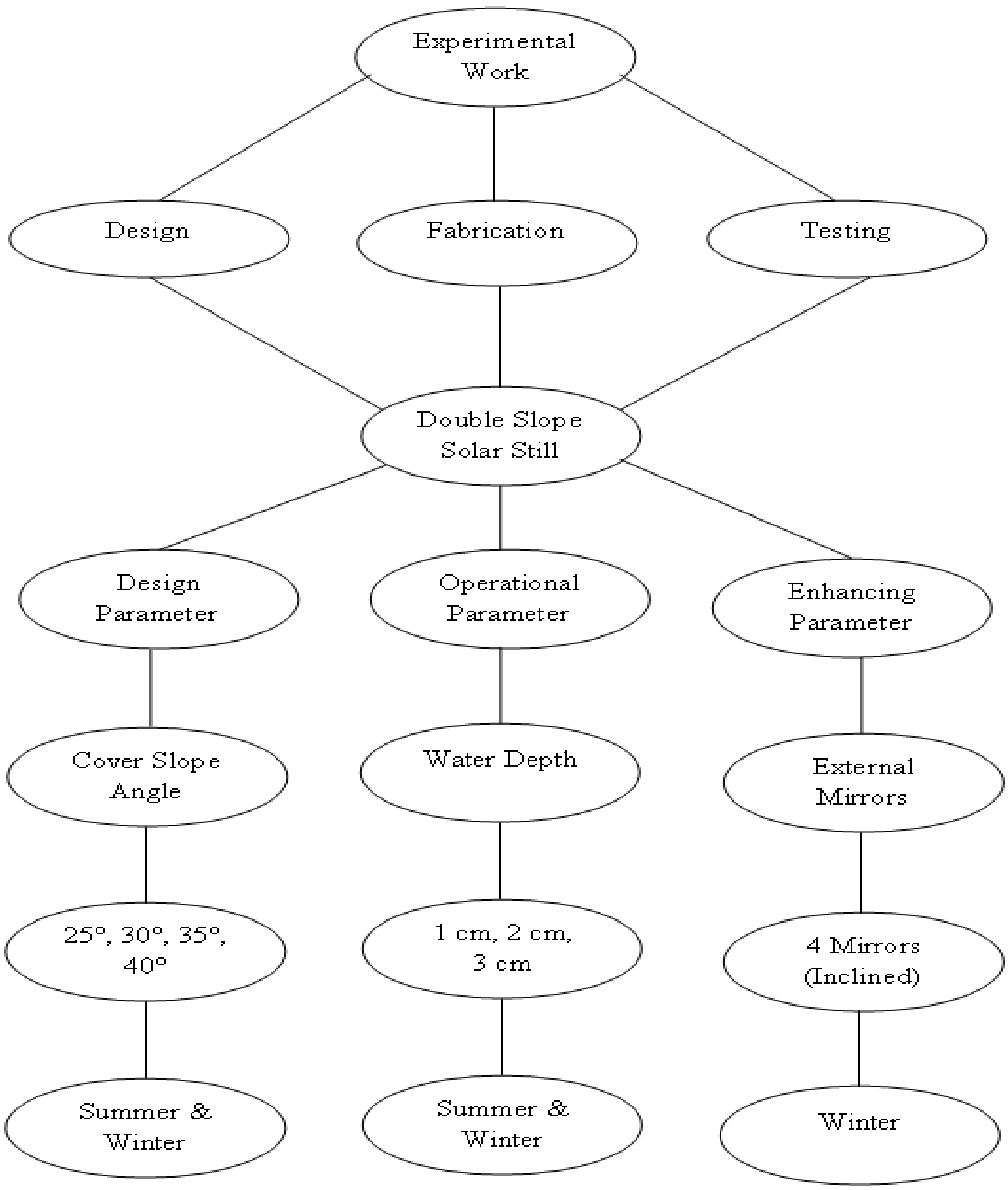

Figure 3.10 Sequence of experimental work

CHAPTER 4

MATHEMATICAL MODEL OF A DOUBLE - SLOPE SOLAR STILL

Mathematical modeling of the solar still was done by considering the various heat transfer mechanisms as shown in Fig 4.1.

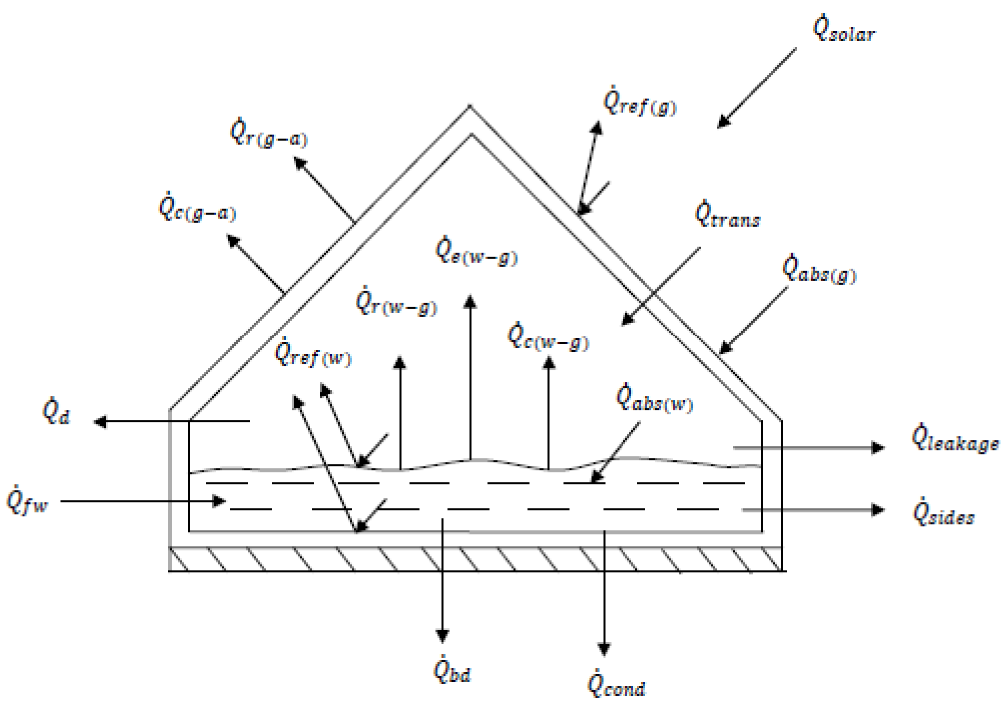

Figure 4.1 Heat transfer modes in a solar still

The solar radiation $\dot{Q}_{solar}$ incident on the still is partly absorbed $\dot{Q}_{abs(g)}$ and reflected $\dot{Q}_{ref(g)}$ by the glass cover while most of it is transmitted $\dot{Q}_{trans}$ through the glass cover into the still. The transmitted radiation $\dot{Q}_{trans}$ from the glass cover is absorbed in large amounts by the basin and the water $\dot{Q}_{abs(w)}$ while a little radiation $\dot{Q}_{ref(w)}$ is again reflected here. The heat gained by the basin water is transferred to the inner glass cover by convection $\dot{Q}_{c(w)}$, radiation $\dot{Q}_{r(w)}$, and evaporation $\dot{Q}_{e(w)}$ of water. Some amount of heat gained by the glass cover in this process is lost to the atmosphere by convection $\dot{Q}_{c(g)}$ and radiation $\dot{Q}_{r(g)}$.

4.1 Energy balance on the solar still

An overall heat and mass balance of the solar still is done by considering the various energy transfer modes into and outside the still through the base tank and the condensing glass covers.

The equation for conservation of mass is written as [32] ,

$$\dot{m}_d = \dot{m}_{fw} - \dot{m}_{bd} \tag{1}$$

where, $\dot{m}_d$ is the mass flow rate of the distilled water and is given by,

$$\dot{m}_d = \frac{\dot{Q}_d}{C_w(T_w - T_{atm})} \tag{2}$$

$\dot{m}_{fw}$ is the mass flow rate of the feed water and is given by,

$$\dot{m}_{fw} = \frac{\dot{Q}_{fw}}{C_w(T_{atm} - T_w)} \tag{3}$$

$\dot{m}_{bd}$ is the mass flow rate of the blow down and is given by,

$$\dot{m}_{bd} = \frac{\dot{Q}_{bd}}{C_w(T_w - T_{atm})} \tag{4}$$

4.2 Energy balance on the glass cover of solar still

An energy balance equation of the glass cover is written as shown below by taking into account the various energy inputs to the still and the heat losses. The energy balance equation for the glass cover is given by [33],

$$(dE_g/dt) = \dot{Q}_{abs,g} + \dot{Q}_{e(w-g)} + \dot{Q}_{c(w-g)} + \dot{Q}_{r(w-g)} - \dot{Q}_{c(g-a)} - \dot{Q}_{r(g-a)} - \dot{Q}_{ref(g-a)} \tag{5}$$

$$(dE_g/dt) = m_g C_g (dT_g/dt) \tag{6}$$

where, $\dot{Q}_{e(w-g)}$ is the heat transfer from water to glass surface due to evaporation;

$\dot{Q}_{c(w-g)}$ is the heat transfer from water to glass surface due to convection;

$\dot{Q}_{r(w-g)}$ is the heat transfer from water to glass surface due to radiation;

$\dot{Q}_{c(g-a)}$ is the heat transfer from glass to atmosphere due to convection;

$\dot{Q}_{r(g-a)}$ is the heat transfer from glass to atmosphere due to radiation.

4.3 Energy balance on the solar still basin

The energy balance equation for the solar still basin and the water contained in it is written as shown below. The energy balance equation for the basin and the water contained in it is given by [33],

$$(dE_{w,b}/dt) = \dot{Q}_{abs,w} + \dot{Q}_{fw} - \dot{Q}_{e(w-g)} - \dot{Q}_{c(w-g)} - \dot{Q}_{r(w-g)} - \dot{Q}_{ref(w,b)} - \dot{Q}_d - \dot{Q}_{bd} - \dot{Q}_l - \dot{Q}_{cond} - \dot{Q}_{sides} \tag{7}$$

$$(dE_{w,b}/dt) = (m_w C_w + m_b C_b)(dT_w/dt) \tag{8}$$

Eqs. (5) and (7) are solved simultaneously for T_w and T_g.

The following assumptions are made while solving the energy balance equations.

1) The temperature of glass is uniform over the glass cover.

2) The temperature of water is uniform over the water and the basin material.

3) Heat loss from the sides and due to leakage of vapor from the still is neglected; thus $\dot{Q}_{leakage}$ and $\dot{Q}_{sides}$ are negligible.

4) Reflection of heat from water surface and the energy storage material used in the basin is negligible, thus $\dot{Q}_{ref(w,b)}$ is negligible.

The distilled water production rate is calculated by [32] ,

$$\dot{m}_d = \dot{Q}_{e(w-g)}/h_{fg} \tag{9}$$

The details of the various terms used in the above equations are given below:

Heat is transferred from water to the glass surface by convection of air trapped inside the still, evaporation of water, and radiation of heat from the water surface. This heat transfer is estimated by [32],

$$\dot{Q}_{c(w-g)} = h_{c(w-g)} A_b (T_w - T_g) \tag{10}$$

$$\dot{Q}_{e(w-g)} = h_{e(w-g)} A_b \left(P_w - P_g\right) \tag{11}$$

$$\dot{Q}_{r(w-g)} = \sigma \varepsilon_{w-g} A_b \left({T_w}^4 - {T_g}^4\right) \tag{12}$$

The convective and evaporative heat transfer coefficients for water to glass surface are calculated by [33] and [32] respectively,

$$h_{c(w-g)} = 0.884 \left[\left(T_w - T_g\right) + \frac{(P_w - P_g)T_w}{268900 - P_w} \right]^{1/3} \tag{13}$$

$$h_{e(w-g)} = \frac{M_w h_{fg} P_T h_{c(w-g)}}{M_a C_{pa} (P_T - P_w)\left(P_T - P_g\right)} \tag{14}$$

The partial vapor pressure at a given basin water temperature T_w and glass surface T_g is found by the relation [34],

$$P_w = 7235 - 431.45T_w + 10.76{T_w}^2 \tag{15}$$

$$P_g = 7235 - 431.45T_g + 10.76{T_g}^2 \tag{16}$$

The specific heat of the air trapped inside the solar still is written in terms of the average temperature of basin water and glass and is known by [35],

$$C_{pa} = 999.2 + (0.14339T_{av}) + \left(0.0001101{T_{av}}^2\right) - (0.67581x10^{-7}{T_{av}}^3) \tag{17}$$

where, $T_{av} = (T_w + T_g)/2$ (18)

The latent heat of evaporation of water is found using [36],

$$h_{fg} = (2503.3 - 2.398T_w) \times 1000 \tag{19}$$

Some amount of heat is absorbed by the glass due to the incident solar radiation falling on the glass surface. This can be calculated by [37],

$$\dot{Q}_{abs,g} = \alpha_g \dot{Q}_S = \alpha_{g,S} A_{g,S} I_S + \alpha_{g,N} A_{g,N} I_N \tag{20}$$

where α_g is the absorptivity of glass.

The solar radiation incident on the still is absorbed in huge amounts by the blackened base and water. The heat absorbed by water is estimated using [37],

$$\dot{Q}_{abs,w} = \alpha_w \dot{Q}_\tau = \alpha_w(\tau_S A_{g,S} I_S + \tau_N A_{g,N} I_N) \tag{21}$$

where α_w is the absorptivity of water.

Heat is absorbed by the glass surface due to evaporation, convection, and radiation from the water surface. Heat is lost from the glass cover to the atmosphere by convection and radiation and is found by [32],

$$\dot{Q}_{c(g-a)} = h_{c(g-a)} A_g \left(T_g - T_{atm}\right) \tag{22}$$

$$\dot{Q}_{r(g-a)} = \sigma \varepsilon_g A_g \left({T_g}^4 - {T_{atm}}^4\right) \tag{23}$$

The convective heat transfer coefficient from glass cover to atmosphere is given by [38],

$$h_{c(g-a)} = 5.7 + 3.8V \tag{24}$$

The heat added to the system by the supply of feed water is written as [32],

$$\dot{Q}_{fw} = \dot{m}_{fw} C_w (T_{atm} - T_w) \tag{25}$$

The heat loss from the system due to the distillate leaving the still is estimated by [32],

$$\dot{Q}_d = \dot{m}_d C_w (T_w - T_{atm}) \tag{26}$$

The heat due to blow down in the base tank is given as [32],

$$\dot{Q}_{bd} = \dot{m}_{bd} C_w (T_w - T_{atm}) \tag{27}$$

The heat loss through the bottom is given by ,

$$\dot{Q}_{cond} = \frac{S_g K_g (T_w - T_{atm})}{L_{gw}} \tag{28}$$

where,

S_g is the shape factor for calculating heat loss to ground;

K_g is the thermal conductivity of soil (W/mK);

and L_{gw} is the width of the solar still (m).

4.4 Calculation of solar radiation on inclined surface

The solar radiation on a tilted surface is a combination of three components and is calculated using Liu and Jordan relation given by [39],

$$I_{Tilted} = I_{beam} R_{beam} + I_{diffuse}\left(\frac{1+cos\beta}{2}\right) + I\rho_{gr}\left(\frac{1-cos\beta}{2}\right) \tag{29}$$

For northern hemisphere, the geometric factor R_{beam} is calculated using [39],

$$R_{beam} = \frac{\cos(\phi-\beta)cos\delta\ cos\omega + \sin(\phi-\beta)sin\delta}{cos\phi\ cos\delta\ cos\omega + sin\phi\ sin\delta} \tag{30}$$

where, β is the glass tilt angle and ρ_{gr} is the ground reflectivity.

The declination angle is found using the equation of Cooper given by [39],

$$\delta = (23.45)\sin\left[\frac{360(284+n)}{365}\right] \tag{31}$$

where, n is the number of the day in the year.

4.5 Addition of external mirrors

The total solar radiation incident on the solar still consists of the global solar radiation incident directly on the glass covers and that reflected by the external mirrors. It can be mathematically expressed as [23],

$$I_{total} = (I_S + I_N) + I_{rmi,S} + I_{rmi,N} + I_{rmi,E} + I_{rmi,W} \quad (32)$$

The solar radiation reflected by the external mirrors can be calculated as [23],

$$I_{rmi,S} = I_{mi,S} \ \rho_{mi} \, F_{mg} \, A_{mi}/(\frac{A_g}{2}) \quad (33)$$

$$I_{rmi,N} = I_{mi,N} \ \rho_{mi} \, F_{mg} \, A_{mi}/(\frac{A_g}{2}) \quad (34)$$

$$I_{rmi,E} = I_{mi,E} \ \rho_{mi} \, F_{mg} \, A_{mi}/(\frac{A_g}{2}) \quad (35)$$

$$I_{rmi,W} = I_{mi,W} \ \rho_{mi} \, F_{mg} \, A_{mi}/(\frac{A_g}{2}) \quad (36)$$

The view factor is expressed as given by [39],

$$F_{mg} = ((cc) + (rr) - S_d)/2(rr) \quad (37)$$

$$S_d{}^2 = ((cc)^2 + (rr)^2 - 2.(cc).(rr).cos\psi) \quad (38)$$

CHAPTER 5

EXPERIMENTAL AND NUMERICAL RESULTS

This chapter presents and compares the experimental results with the results obtained by the numerical model. Few assumptions were made with which the numerical simulation showed close agreement with the experimental results.

A computer program was written in MATLAB software and solved using ‘ode23’ function. Simulation was carried out for all the cases with varying glass tilt angles and water depths and the results obtained are shown below for summer and winter seasons. Numerical simulations were done using the same weather conditions on typical summer and winter days. Some of the obtained results are presented in this chapter.

The geographical and design parameters of the experimental site are given below.

Latitude 26°15´N

Longitude 50°09´E

Elevation (above mean sea level) 84 ft/26 m

Ambient Temperature 40 °C (average temperature for a typical day in June)

Wind Velocity 5 m/s (average velocity for a typical day in June)

Ambient Temperature 21 °C (average temperature for a typical day in December)

Wind Velocity 2 m/s (average velocity for a typical day in December)

5.1 Summer Results

5.1.1 Effect of cover slope angle

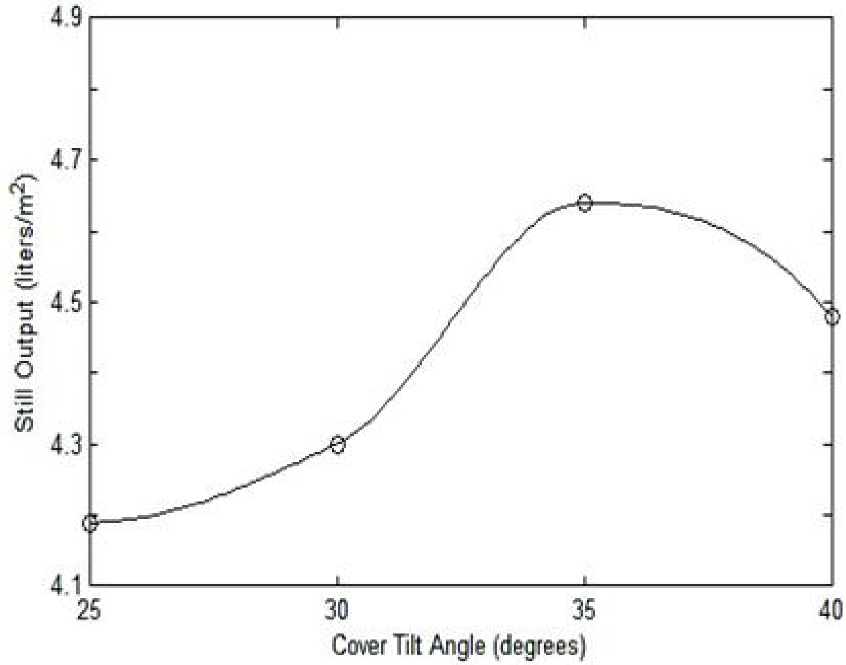

Figure 5.1 Experimental productivities for different cover tilt angles

Fig 5.1 shows the performance of a solar still on a typical day in June with 1 cm water depth. The productivity of the still increases from 25° to 35° glass slope angle and it decreases for 40° angle. Hence the best tilt angle of the glass cover is found to be 35° with a maximum productivity of 4.64 l/m^2.

This is in strong agreement to a very recent study done by Dev et al. [14] wherein the glass tilt angle for best performance is not found to be equal to the latitude angle. The productivity increased by 2.6% as the glass tilt angle was increased from 25° to 30° and by 7.9% when the angle is changed from 30° to 35°. Further, there was a reduction in productivity by 3.4% when the tilt angle was increased from 35° to 40°. This can be attributed to the reduction in solar radiation on north and south faces of the solar still with high glass tilt angles because the angle of incidence of solar radiation changes with change in glass tilt angle. Fig 5.2 shows the variation of ambient temperature with time.

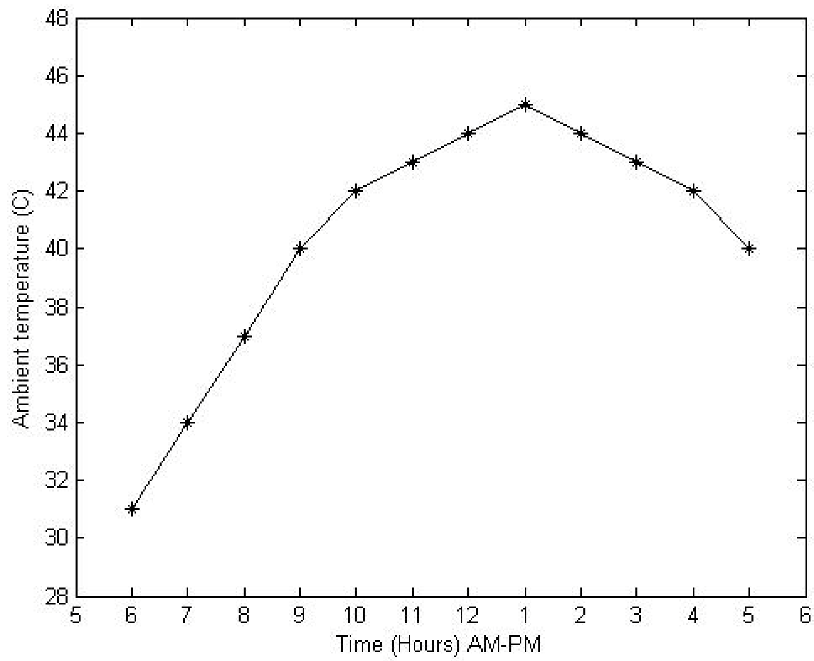

Figure 5.2 Hourly variation of ambient temperature on 24 June 2009

During the day from sunrise to sunset, the ambient temperature and hence solar radiation increases gradually and reaches a certain maximum value at around noon and then it decreases. After sunrise, the saline water in the base tank heats up and condensation takes place at the inner glass surface. The glass covers allows the solar radiation to pass through them and traps the solar energy inside the still. Due to this process of evaporation, the salts and other bacteria are left behind in the basin while the water evaporates. When the condensate drops reaches its threshold size, they start flowing downward under the influence of gravity and the distilled water thus obtained is collected. From sunset to next day sunrise, the temperature of the still components was close to the ambient temperature. The temperature profiles for the basin water and the glass cover is shown in the Figs 5.3, 5.6, 5.9 and 5.12. The wind speed was observed to be changing randomly throughout the day.

The high productivity obtained in summer is due to the high absorption of heat by the black painted G.I steel which leads to increase in the saline water temperature. The ambient wind cools the glass cover of the still which increases the convection and radiation from the glass covers resulting in lower glass cover temperature. This in turn leads to higher condensate rate and hence high productivity. The productivity of the solar still increases with increase in temperature difference between the basin water and the glass cover temperatures.

Table 5.1 Experimental observations of accumulated productivity on June 24, 2009

Time (AM-PM)	Ambient Temperature (°C)	Wind Speed (m/s)	Accumulated Productivity (liters/m^2)			
			25°	30°	35°	40°
6:00	31	2.6	0.000	0.000	0.000	0.000
7:00	34	2.1	0.018	0.019	0.020	0.019
8:00	37	1.5	0.061	0.066	0.078	0.070
9:00	40	7.2	0.313	0.335	0.375	0.352
10:00	42	7.2	0.775	0.805	0.872	0.830
11:00	43	6.2	1.335	1.373	1.456	1.406
12:00	44	7.2	1.921	1.977	2.120	2.046
1:00	45	7.2	2.526	2.601	2.795	2.707
2:00	44	7.2	3.098	3.188	3.433	3.325
3:00	43	7.2	3.589	3.694	3.985	3.850
4:00	42	7.2	3.961	4.069	4.400	4.242
5:00	40	7.2	4.192	4.306	4.649	4.485

Table 5.2 Experimental observations of glass temperatures on June 24, 2009

Time (AM-PM)	*Glass Temperature (°C)*			
	25°	**30°**	**35°**	**40°**
6:00	29.0	29.0	29.0	29.0
7:00	31.3	32.0	33.3	32.6
8:00	39.9	41.1	39.4	38.7
9:00	45.3	45.5	48.0	46.2
10:00	50.4	51.6	50.6	49.1
11:00	53.0	54.2	55.5	53.9
12:00	54.3	55.3	56.5	54.8
1:00	54.6	55.8	56.9	55.2
2:00	52.8	53.1	53.2	52.6
3:00	51.3	51.6	51.7	51.4
4:00	46.5	46.2	46.5	45.8
5:00	43.0	43.2	44.4	42.9

Table 5.3 Experimental observations of water temperatures on June 24, 2009

Time (AM-PM)	***Water Temperature (°C)***			
	25°	**30°**	**35°**	**40°**
6:00	26.0	26.0	26.0	26.0
7:00	32.2	32.9	33.0	33.5
8:00	43.3	44.4	41.6	42.0
9:00	50.5	51.6	52.9	51.2
10:00	55.2	54.3	55.5	53.9
11:00	57.3	58.5	59.8	58.2
12:00	58.1	59.2	60.7	59.1
1:00	59.4	60.6	61.8	60.2
2:00	57.2	57.3	59.4	57.0
3:00	55.5	55.9	55.2	55.5
4:00	50.1	49.6	49.8	50.2
5:00	46.5	46.8	46.2	46.5

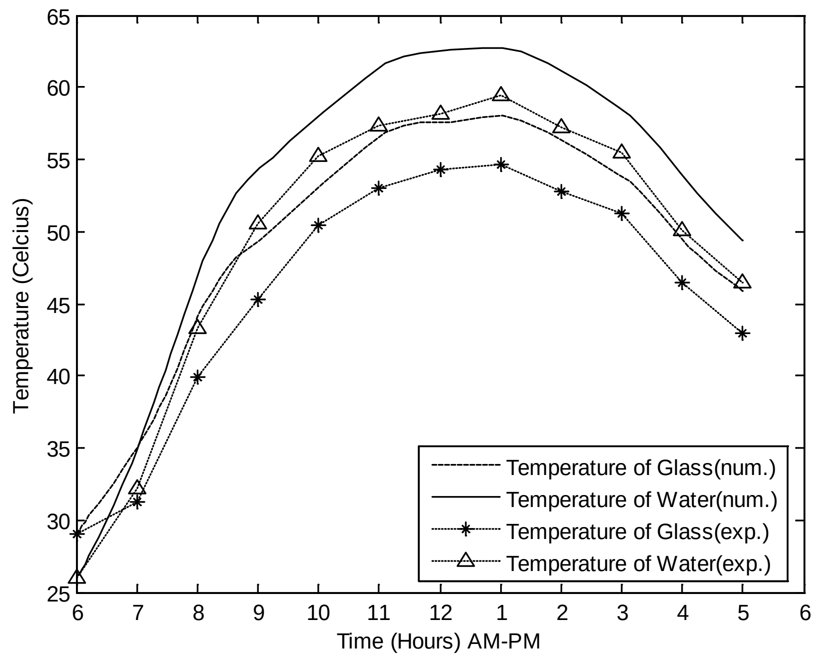

Figure 5.3 Comparison of temperature profiles for 25° cover slope angle

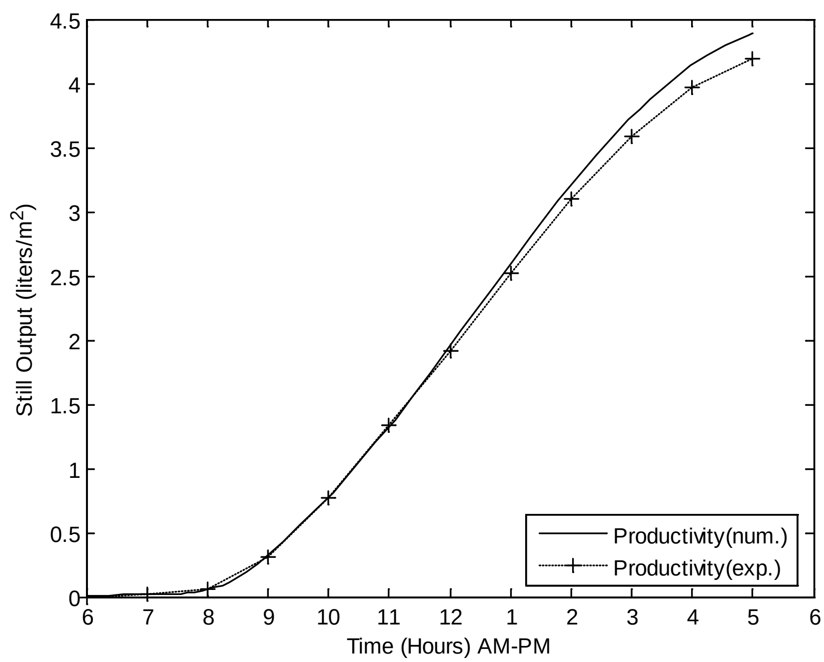

Figure 5.4 Comparison of daily productivity for 25° cover slope angle

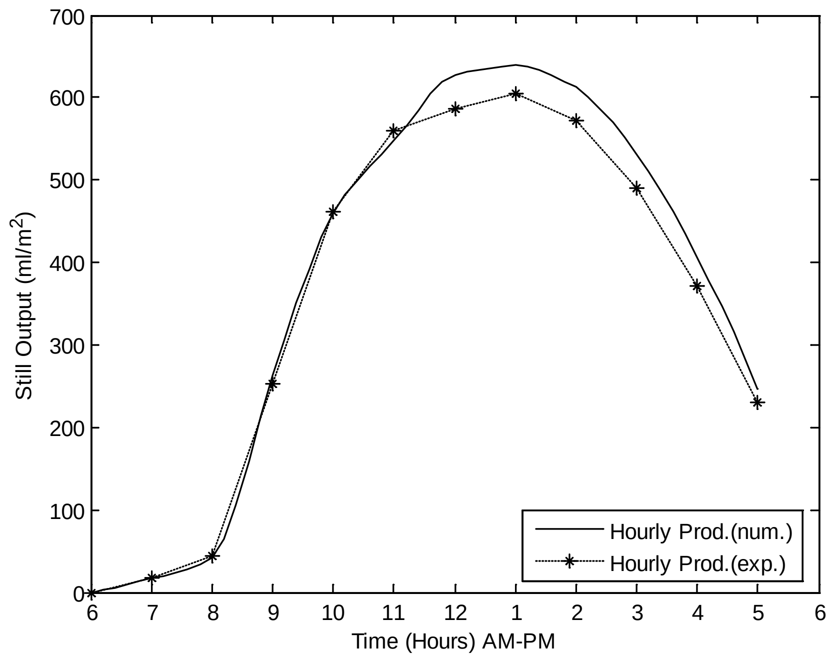

Figure 5.5 Comparison of hourly productivity for 25° cover slope angle

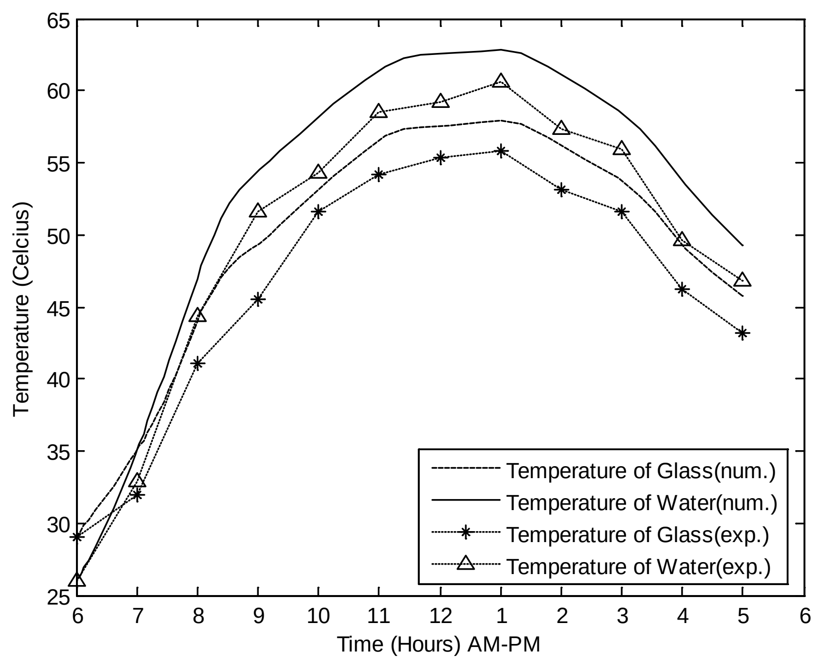

Figure 5.6 Comparison of temperature profiles for 30° cover slope angle

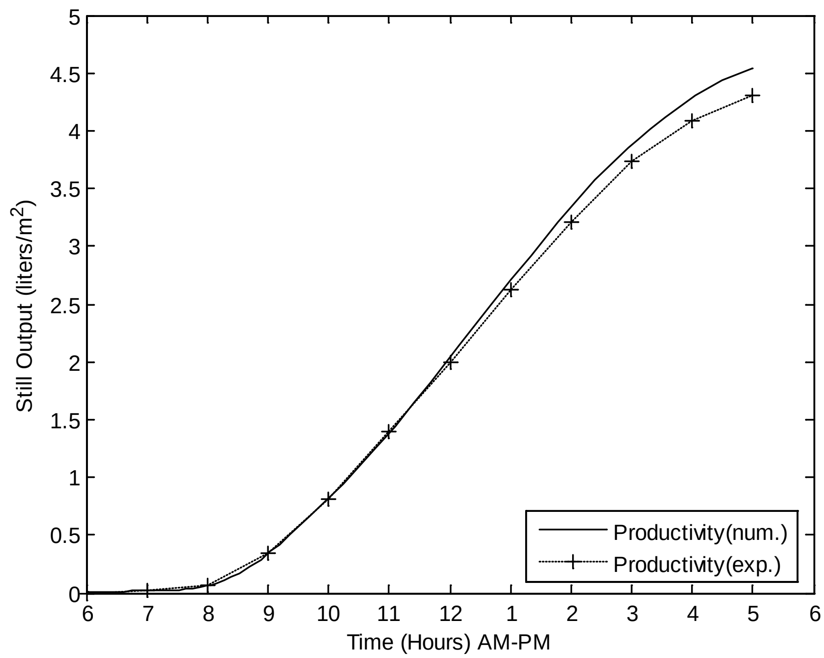

Figure 5.7 Comparison of daily productivity for 30° cover slope angle

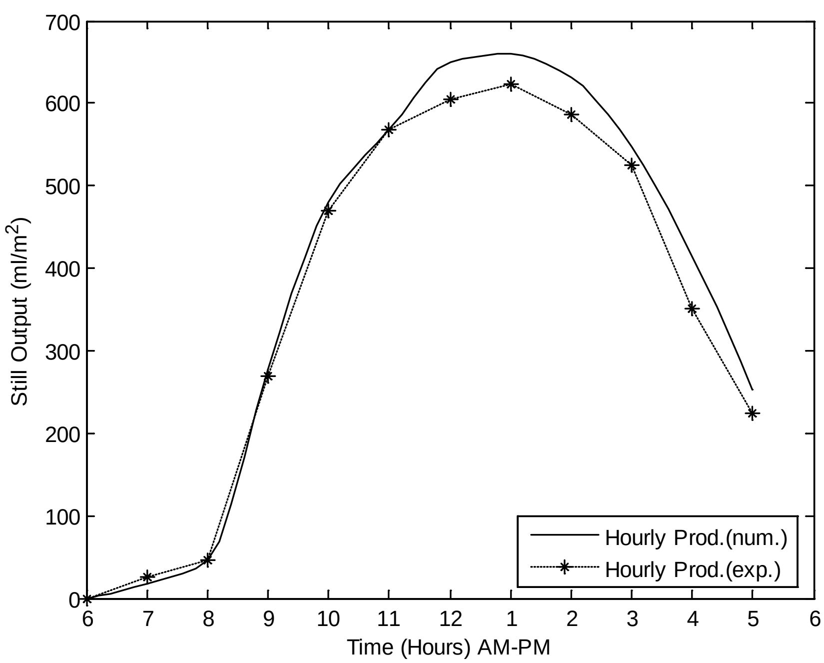

Figure 5.8 Comparison of hourly productivity for 30° cover slope angle

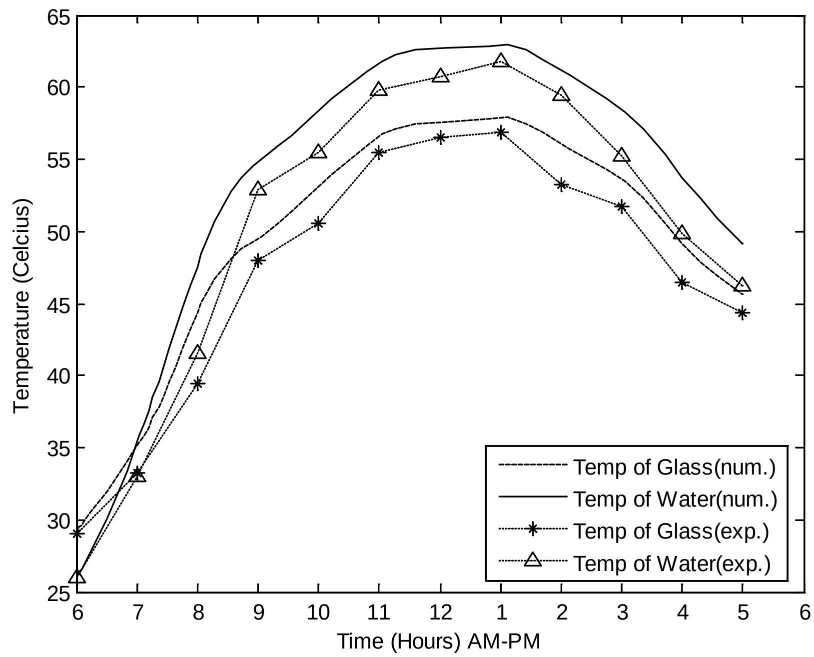

Figure 5.9 Comparison of temperature profiles for 35° cover slope angle

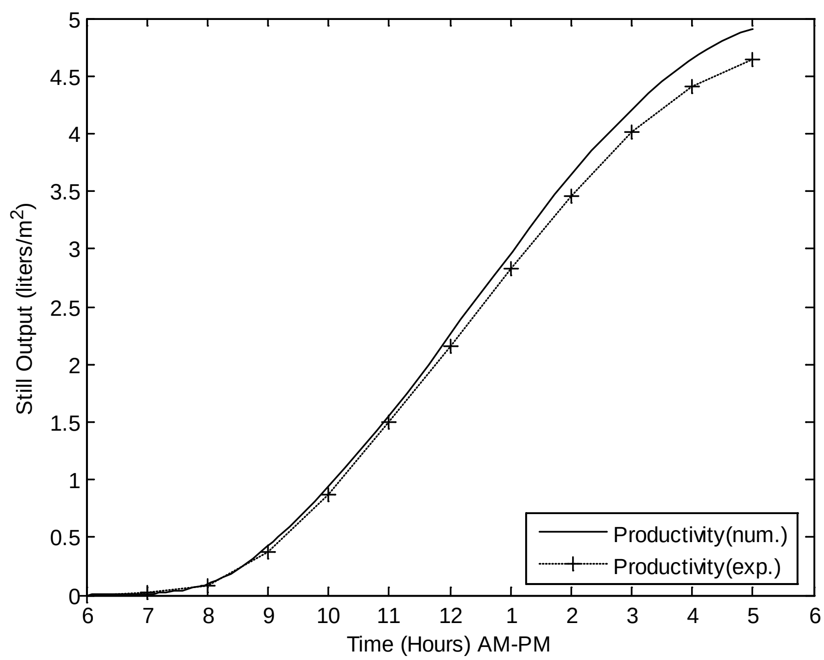

Figure 5.10 Comparison of daily productivity for 35° cover slope angle

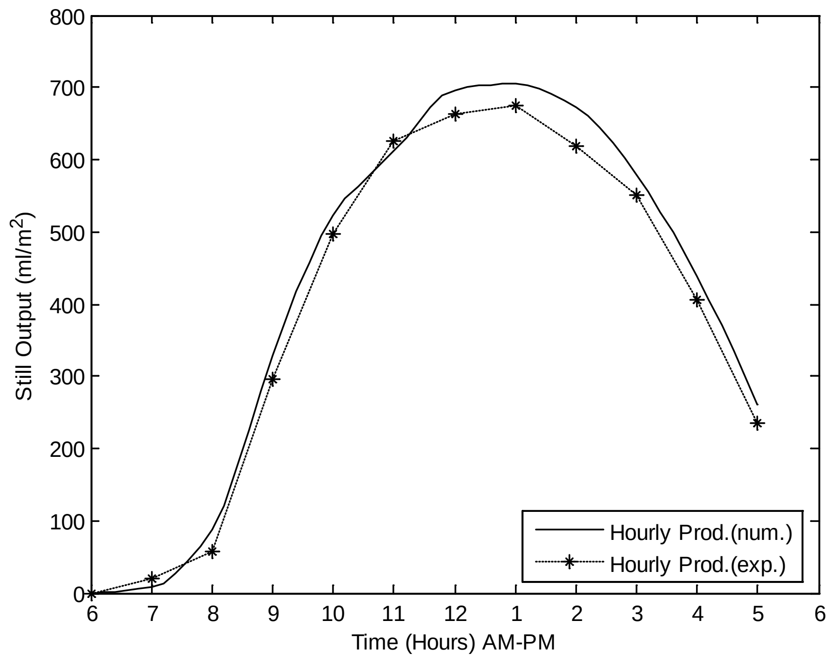

Figure 5.11 Comparison of hourly productivity for 35° cover slope angle

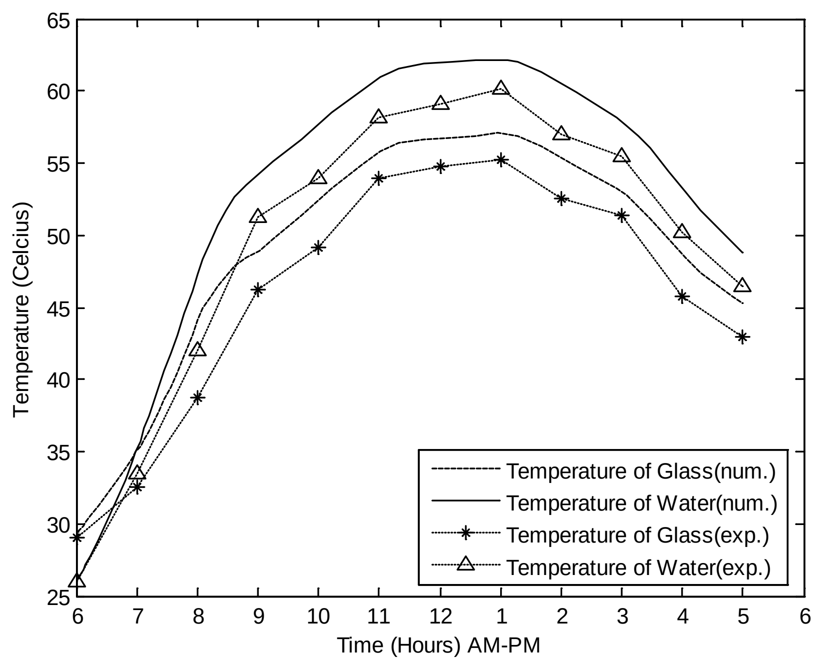

Figure 5.12 Comparison of temperature profiles for 40° cover slope angle

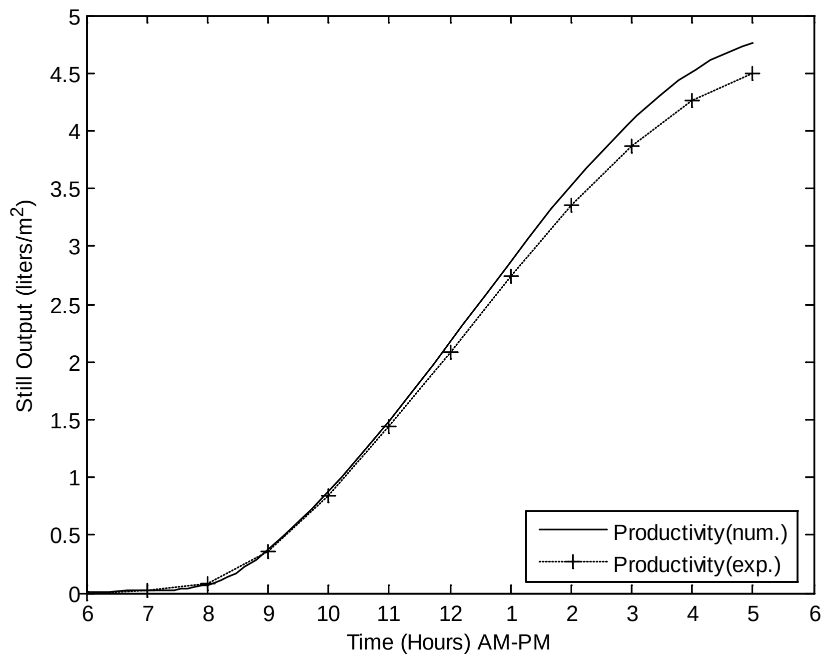

Figure 5.13 Comparison of daily productivity for 40° cover slope angle

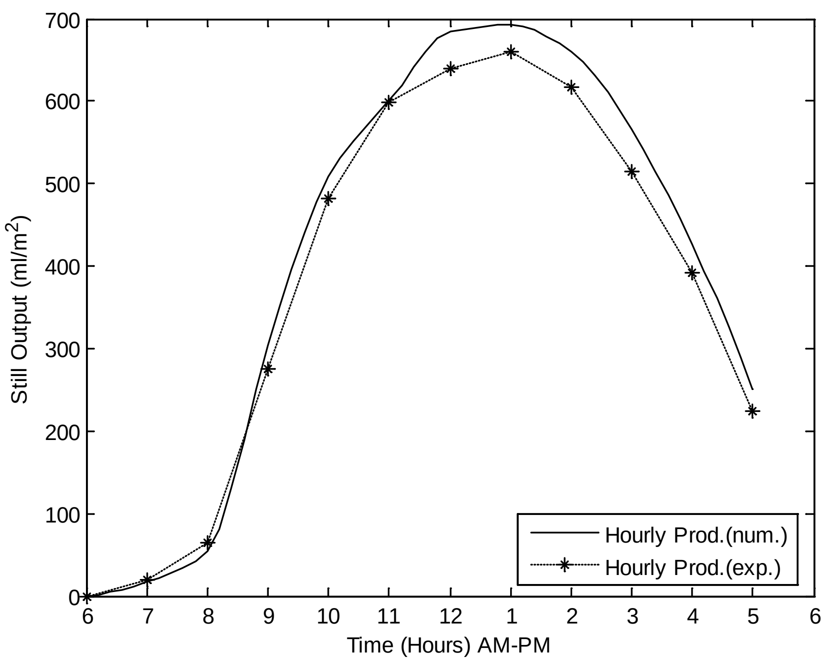

Figure 5.14 Comparison of hourly productivity for 40° cover slope angle

5.1.2 Effect of water depth

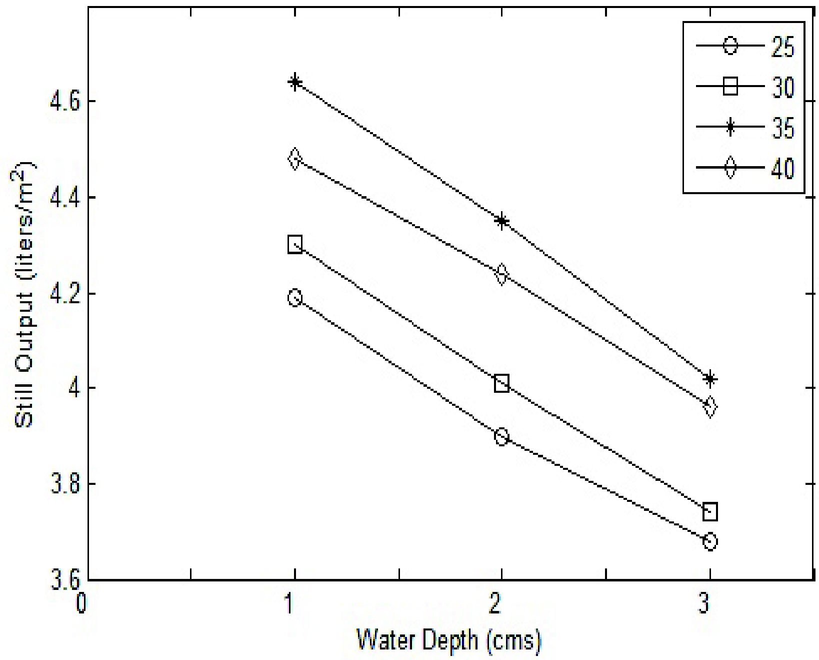

Figure 5.15 Experimental productivities for different slope angles and water depths

Three different water depths were tested for June as seen from Fig 5.15. As expected, when the water depth was increased from 1 cm to 3 cm, the productivity decreased. Several researchers [8-9, 11, 13-15] have found the same effect of water depth on productivity, i.e.; the smaller depth yielding the maximum output. When the water depth is increased, the heat capacity of the water is increased. This will reduce the basin water and glass temperatures which ultimately decreases the evaporation rate. This results in decrease in productivity for high water depths. For all the water depths considered, 35° glass tilt angle gave the best results. For this particular still which has an best tilt angle, the productivity decreased by 6.2% when the water depth was increased from 1 cm to 2 cm, , whereas from 2 cm to 3 cm, a decrease of 6.7% was observed .

The evaporation of water inside the still is increased by the increase in basin water temperature. The motion of the air mixture inside the still is increased by the temperature difference between the water and the glass surface which will result in increased condensation. The productivity of the solar still is found to be a function of basin water and glass temperatures.

Of all the temperatures, the basin water temperature was found to be highest as most of the solar energy is absorbed there. The water temperature reached a maximum value at around 1:00 PM.

Table 5.4 Experimental observations of accumulated productivity on June 25, 2009

Time (AM-PM)	Ambient Temperature (°C)	Wind Speed (m/s)	Accumulated Productivity (liters/m^2) Cover Slope Angle : 35°		
			1 cm	2 cm	3 cm
6:00	30	3.1	0.000	0.000	0.000
7:00	34	4.6	0.020	0.007	0.000
8:00	38	4.1	0.078	0.022	0.004
9:00	41	4.7	0.375	0.177	0.083
10:00	44	4.7	0.872	0.551	0.348
11:00	46	4.6	1.456	1.070	0.770
12:00	47	3.1	2.120	1.690	1.329
1:00	46	5.1	2.795	2.360	1.954
2:00	46	5.1	3.433	3.008	2.592
3:00	45	5.1	3.985	3.568	3.187
4:00	44	5.1	4.400	4.048	3.695
5:00	39	4.1	4.649	4.356	4.054

Table 5.5 Experimental observations of glass temperatures on June 25, 2009

Time (AM-PM)	***Glass Temperature (°C)***		
	1 cm	**2 cm**	**3 cm**
6:00	32.0	32.0	32.0
7:00	33.3	34.2	33.6
8:00	39.4	37.6	36.5
9:00	48.0	44.2	43.4
10:00	50.6	48.1	46.5
11:00	55.5	53.0	52.7
12:00	56.5	54.5	54.8
1:00	56.9	56.1	55.9
2:00	53.2	53.8	53.6
3:00	51.7	50.5	50.2
4:00	46.5	46.2	45.3
5:00	44.4	43.8	43.2

Table 5.6 Experimental observations of water temperatures on June 25, 2009

Time (AM-PM)	***Water Temperature (°C)***		
	1 cm	**2 cm**	**3 cm**
6:00	30.0	30.0	30.0
7:00	33.0	33.3	33.5
8:00	41.6	39.7	38.6
9:00	52.9	48.8	47.2
10:00	55.5	53.1	52.1
11:00	59.8	58.0	57.5
12:00	60.7	59.6	59.1
1:00	61.8	61.2	60.8
2:00	59.4	59.0	59.0
3:00	55.2	55.5	54.2
4:00	49.8	49.5	48.8
5:00	46.2	45.5	45.3

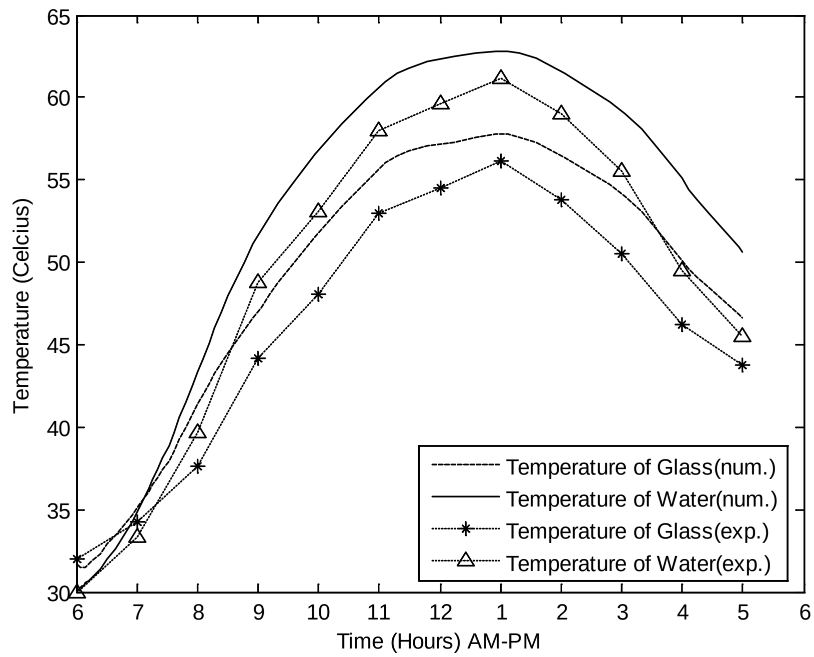

Figure 5.16 Comparison of temperature profiles for 35° slope angle and 2 cm depth

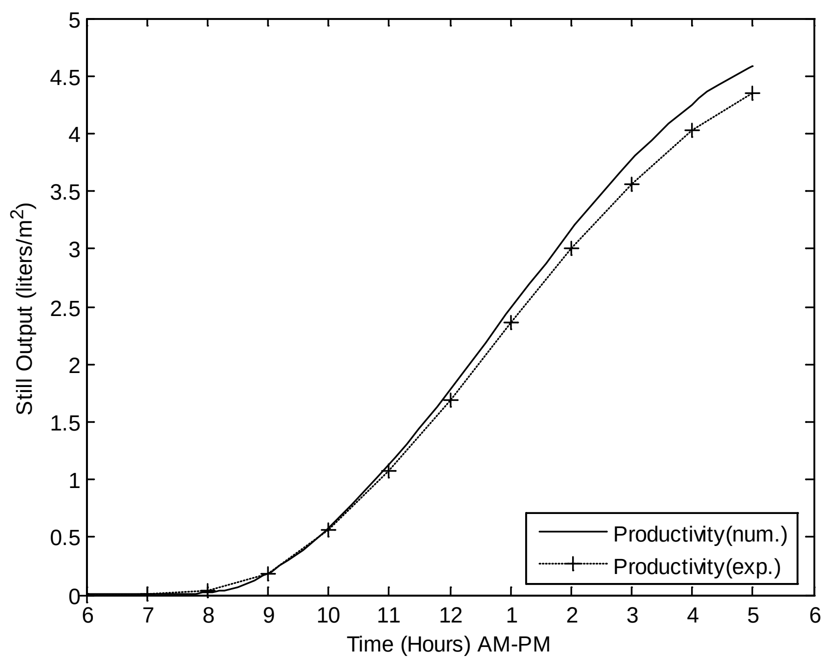

Figure 5.17 Comparison of daily productivity for 35° slope angle and 2 cm depth

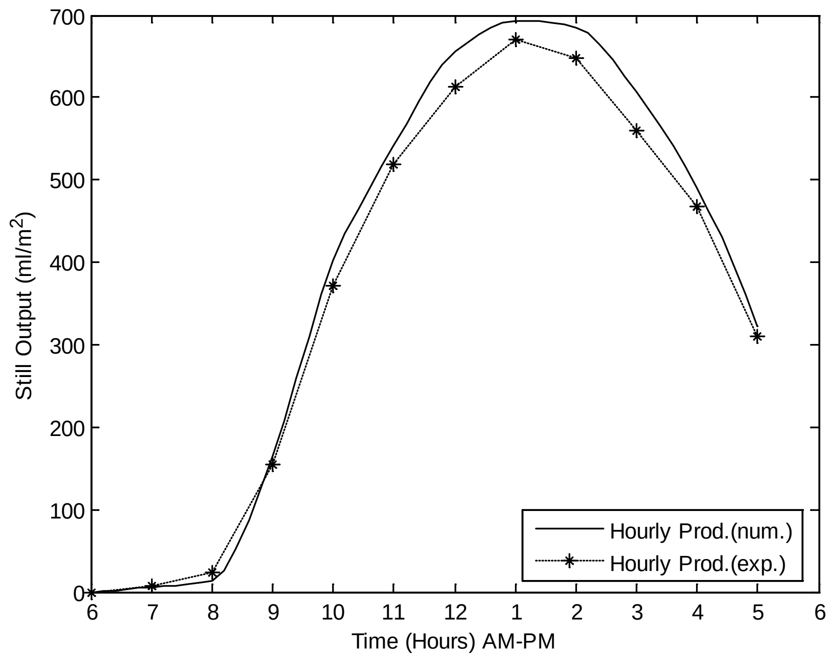

Figure 5.18 Comparison of hourly productivity for 35° slope angle and 2 cm depth

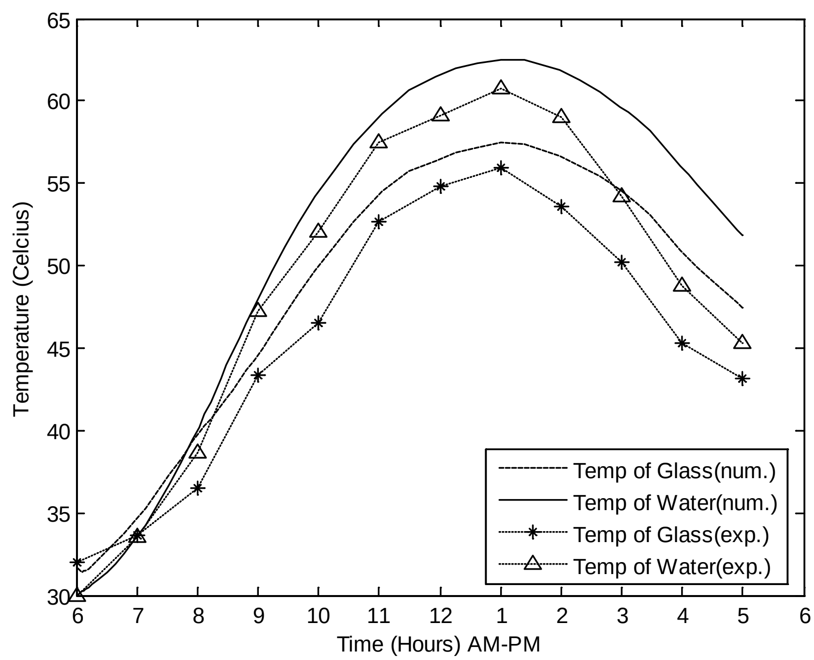

Figure 5.19 Comparison of temperature profiles for 35° slope angle and 3 cm depth

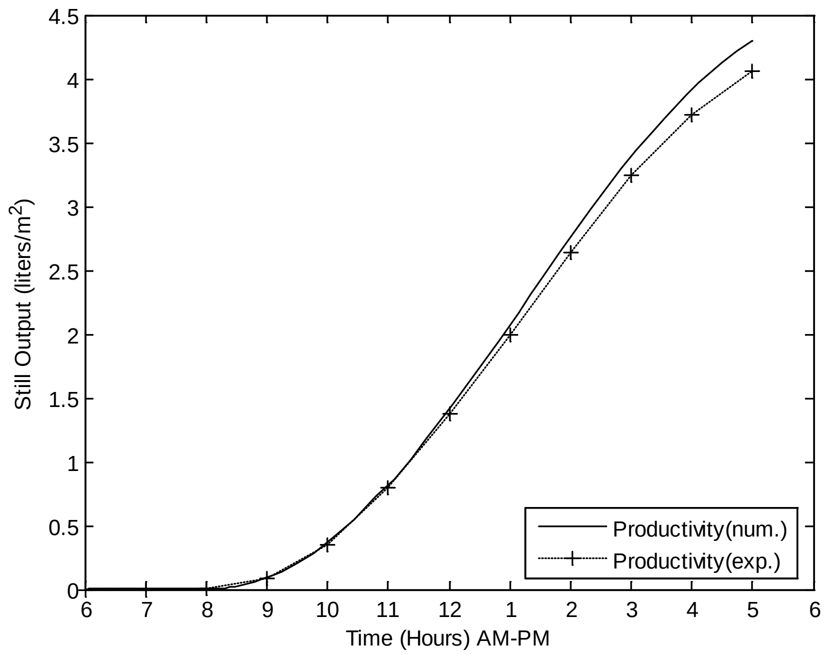

Figure 5.20 Comparison of daily productivity for 35° slope angle and 3 cm depth

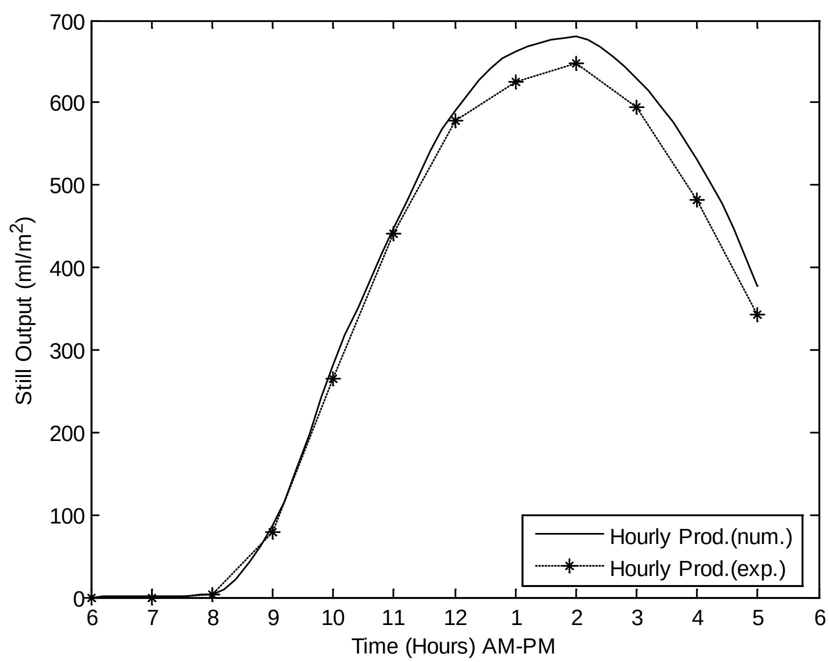

Figure 5.21 Comparison of hourly productivity for 35° slope angle and 3 cm depth

5.2 Winter Results

5.2.1 Effect of cover slope angle

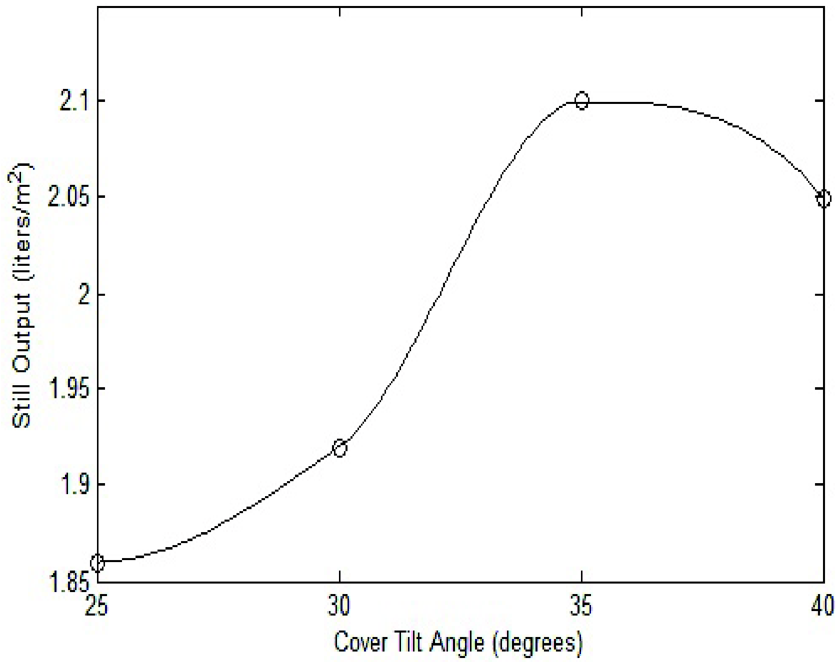

Figure 5.22 Experimental productivities for different cover tilt angles

Fig 5.22 shows the performance of a solar still on a typical day in December with 1 cm water depth. It can be observed that a similar trend is obtained in winter, and the best tilt angle was again found to be 35° with a maximum productivity of 2.1 l/m^2. This result is also in agreement with [14] wherein the optimum angle obtained for winter is the same as that of summer .The productivity increased by 3.2% from 25° to 30° glass tilt angle where as an increase of 9.3% was observed from 30° to 35° variation in slope angle. A reduction of 2.3% in productivity was found when the angle was further increased to 40°.

Fig. 5.23 shows the hourly variation of atmospheric temperature for a typical day in winter. In the initial stages of the solar still operation just before sunrise, the glass cover temperature was observed to be more than the basin water temperature. But with increase in solar radiation along the day, the water temperature is higher than the glass temperature as can be seen in Fig 5.24.

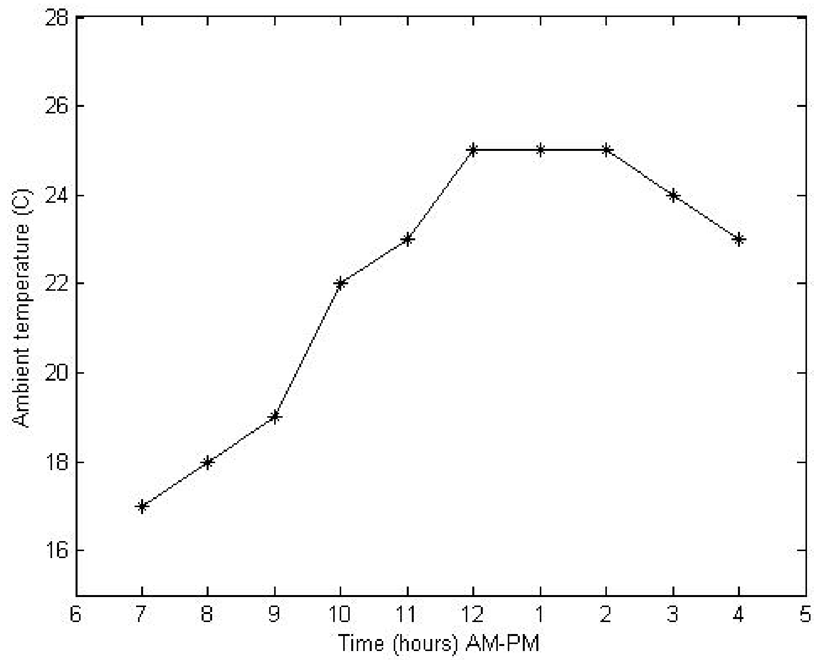

Figure 5.23 Hourly variation of ambient temperature on 05 December 2009

Table 5.7 Experimental observations of accumulated productivity on Dec. 05, 2009

Time (AM-PM)	Ambient Temperature (°C)	Wind Speed (m/s)	Accumulated Productivity (liters/m^2)			
			25°	30°	35°	40°
7:00	17	1.5	0.000	0.000	0.000	0.000
8:00	18	1.5	0.004	0.004	0.004	0.004
9:00	19	1.0	0.017	0.019	0.022	0.022
10:00	22	2.1	0.122	0.129	0.148	0.147
11:00	23	1.0	0.362	0.379	0.424	0.405
12:00	25	1.5	0.674	0.700	0.779	0.752
1:00	25	1.0	1.009	1.052	1.165	1.130
2:00	25	3.6	1.404	1.458	1.600	1.556
3:00	24	2.5	1.691	1.752	1.916	1.866
4:00	23	3.6	1.865	1.928	2.105	2.051

Table 5.8 Experimental observations of glass temperatures on Dec. 05, 2009

Time (AM-PM)	***Glass Temperature (°C)***			
	25°	**30°**	**35°**	**40°**
7:00	16.0	16.0	16.0	16.0
8:00	17.0	17.6	18.6	18.0
9:00	21.5	21.5	22.7	22.1
10:00	28.9	28.2	28.6	27.9
11:00	37.0	37.4	38.5	38.0
12:00	40.6	41.0	42.2	41.5
1:00	42.2	42.1	43.6	42.8
2:00	34.5	33.9	37.3	34.5
3:00	32.2	31.2	32.3	31.7
4:00	25.3	25.8	29.4	25.5

Table 5.9 Experimental observations of water temperatures on Dec. 05, 2009

Time (AM-PM)	***Water Temperature (°C)***			
	25°	**30°**	**35°**	**40°**
7:00	14.0	14.0	14.0	14.0
8:00	17.5	18.5	19.6	19.0
9:00	25.1	26.5	27.9	27.2
10:00	34.8	34.6	35.1	34.3
11:00	42.4	43.2	44.5	43.8
12:00	45.2	46.0	46.3	46.6
1:00	47.0	47.9	49.4	48.6
2:00	41.8	41.6	42.9	42.2
3:00	37.9	37.7	38.8	38.3
4:00	31.3	32.3	35.6	32.0

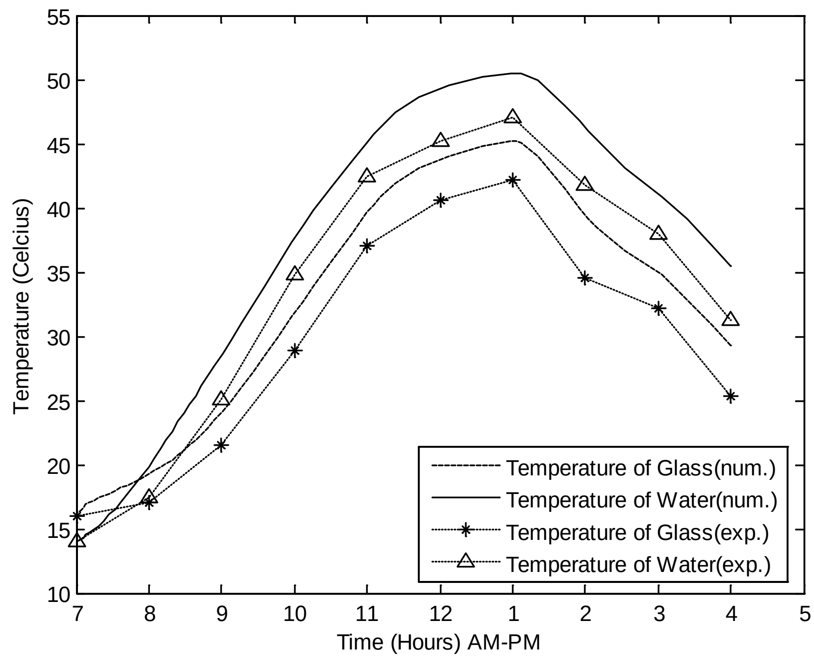

Figure 5.24 Comparison of temperature profiles for 25° cover slope angle

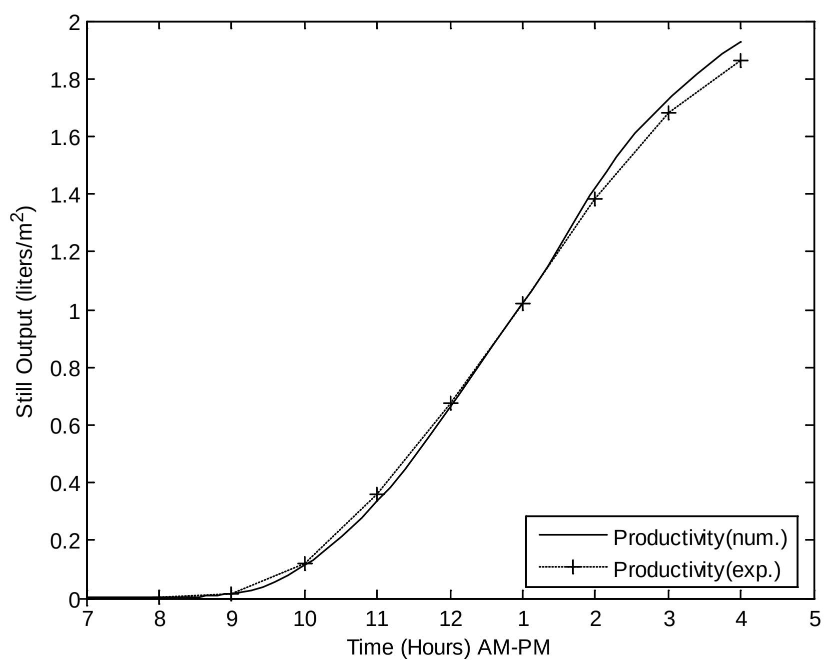

Figure 5.25 Comparison of daily productivity for 25° cover slope angle

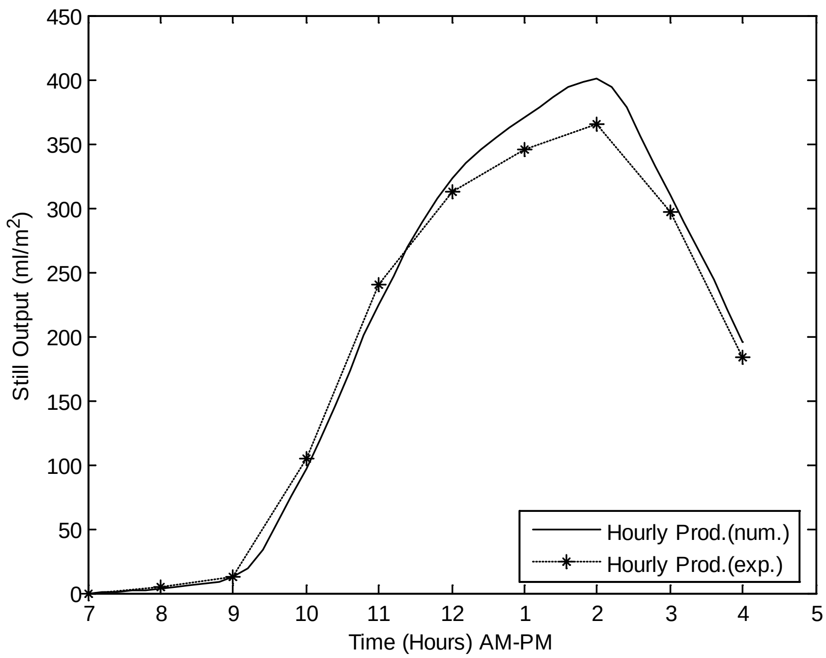

Figure 5.26 Comparison of hourly productivity for 25° cover slope angle

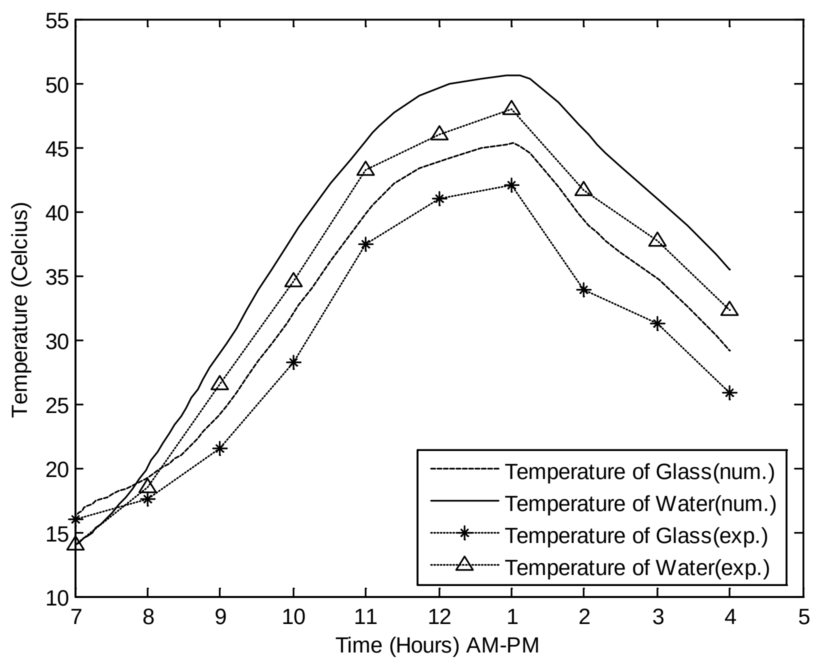

Figure 5.27 Comparison of temperature profiles for 30° cover slope angle

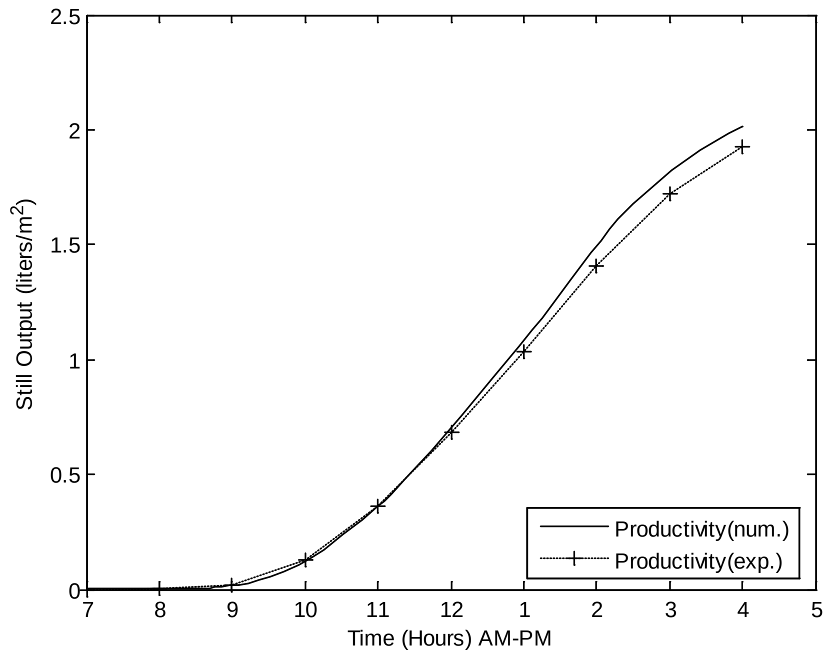

Figure 5.28 Comparison of daily productivity for 30° cover slope angle

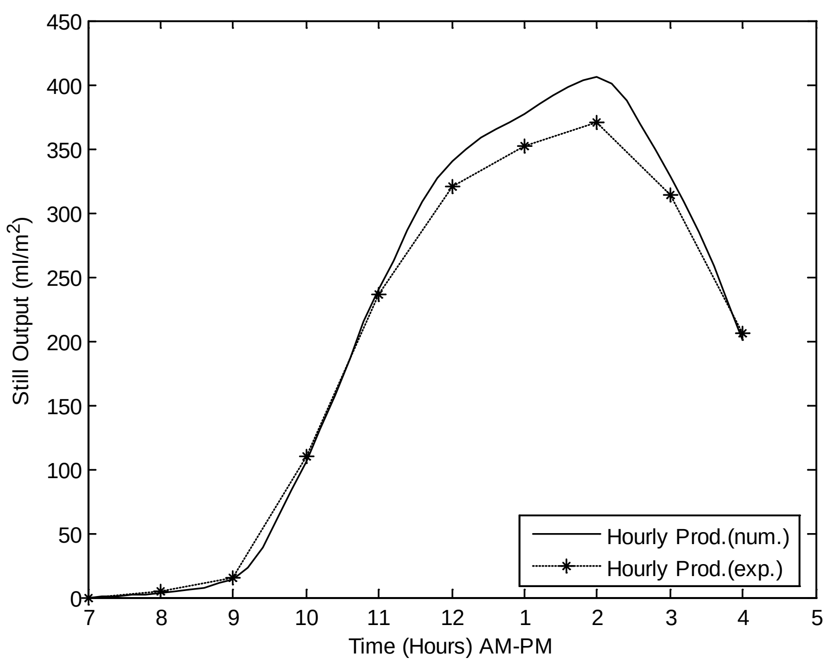

Figure 5.29 Comparison of hourly productivity for 30° cover slope angle

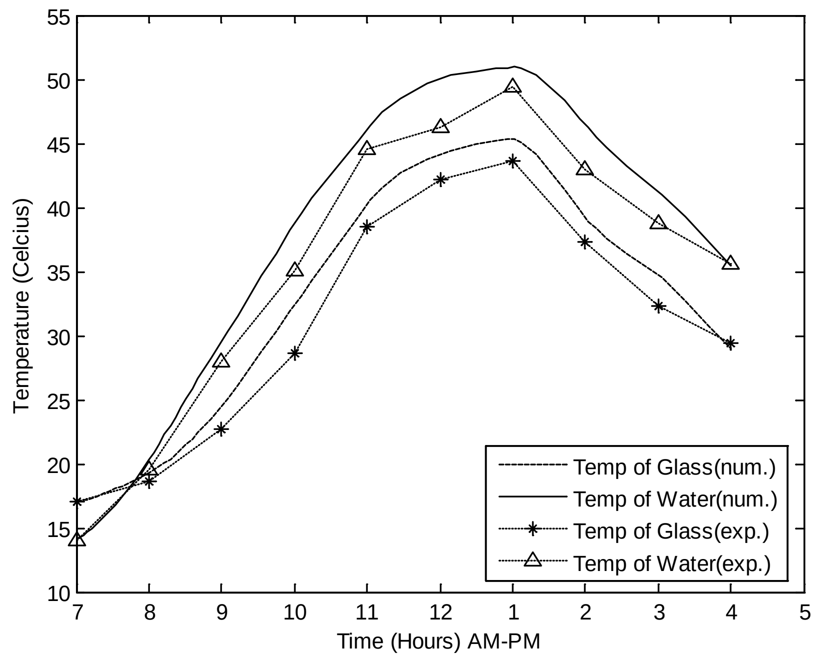

Figure 5.30 Comparison of temperature profiles for 35° cover slope angle

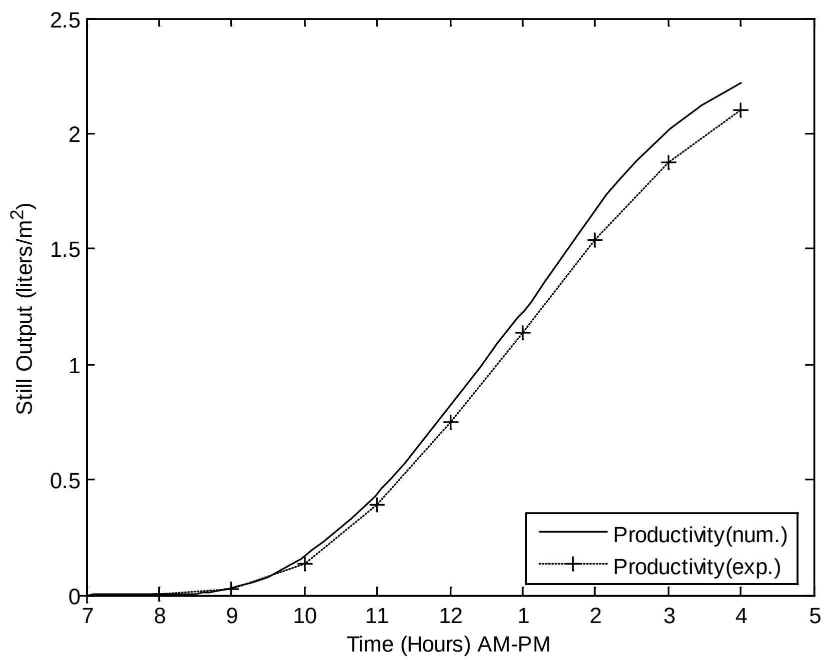

Figure 5.31 Comparison of daily productivity for 35° cover slope angle

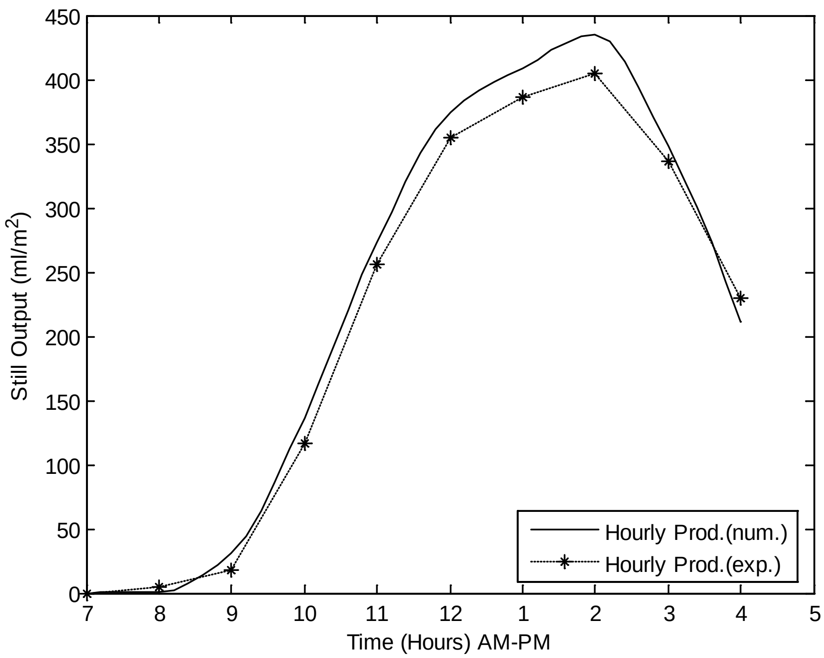

Figure 5.32 Comparison of hourly productivity for 35° cover slope angle

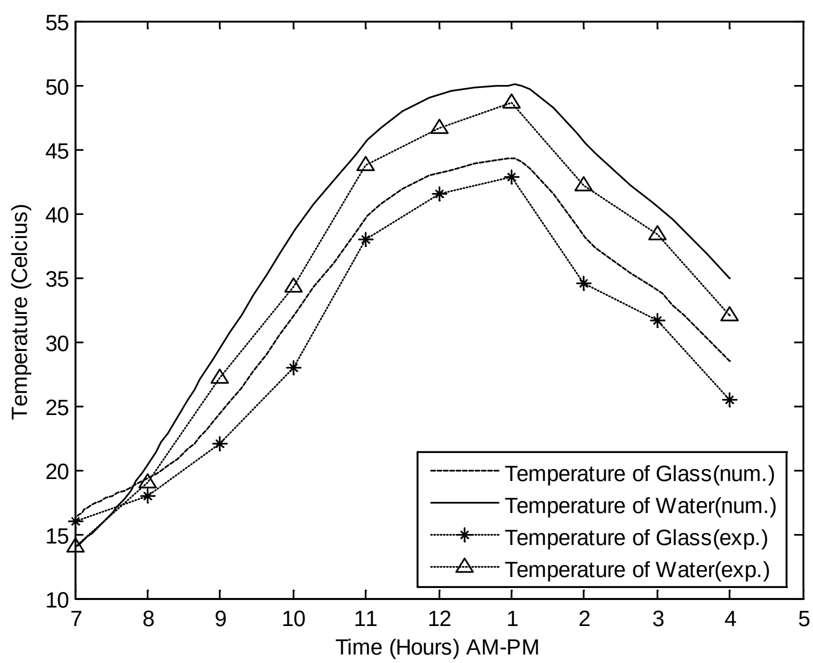

Figure 5.33 Comparison of temperature profiles for 40° cover slope angle

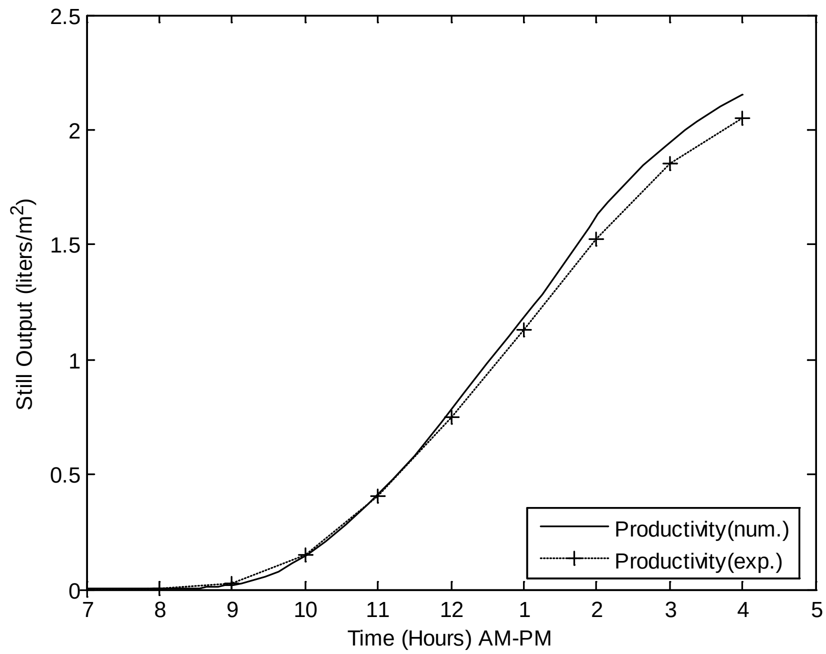

Figure 5.34 Comparison of daily productivity for 40° cover slope angle

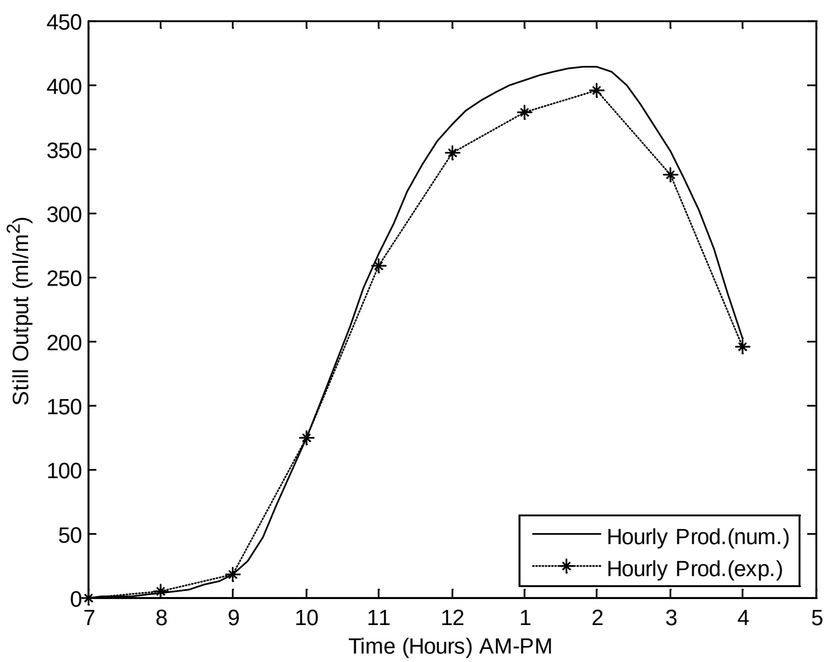

Figure 5.35 Comparison of hourly productivity for 40° cover slope angle

5.2.2 Effect of water depth

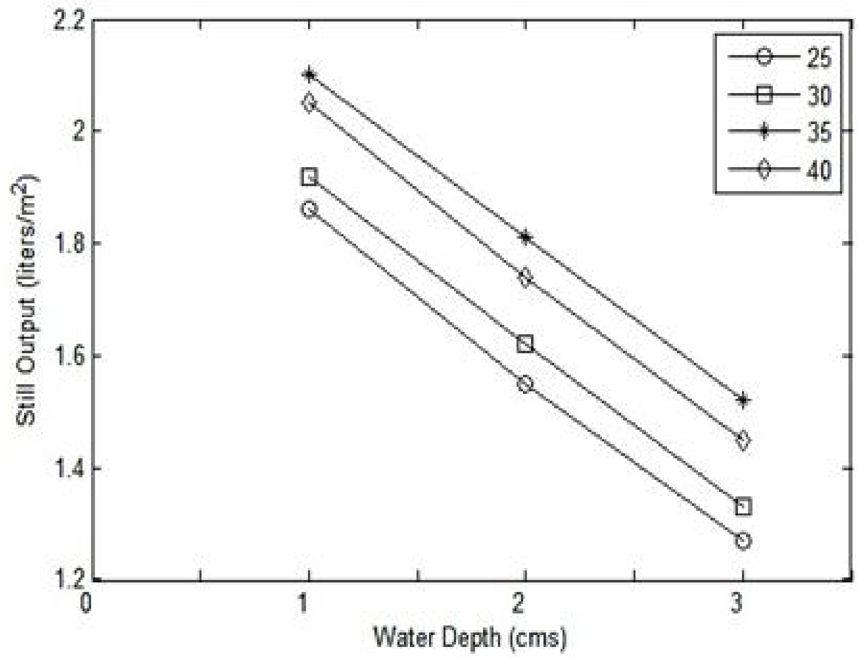

Figure 5.36 Experimental productivities for different slope angles and water depths

The same water depths were again tested for December as seen in Fig 5.36. The effect of water depth on the productivity of solar still in winter was found to be the same as that of summer, i.e.; with increase in water depth, there is a decrease in productivity. With decrease in water depth, there is an increase in the basin water temperature, which increases the evaporation rate of water. As a result of this, the condensation of water increases and hence the productivity increases for lower water depths. A maximum output of 2.10 l/m^2 was obtained at 1 cm depth for 35° tilt angle. The output reduced by 13.8% and 16% for 2 cm and 3 cm water depths respectively.

Since the solar energy is low in morning, the productivity is very less as much of the available energy is consumed in warming up of the still. With the passage of time, the productivity increases to a peak value and then it begins to decrease.

Figs 5.37 and 5.40 show the hourly variation of glass and basin water temperatures. As seen in these figures, the temperatures have the same trend, as they increase in the morning to a peak value after which they start to decrease late in the afternoon.

Table 5.10 Experimental observations of accumulated productivity on Dec. 06, 2009

Time (AM-PM)	Ambient Temperature (°C)	Wind Speed (m/s)	Accumulated Productivity (liters/m^2) Cover Slope Angle : 35°		
			1 cm	2 cm	3 cm
7:00	20	4.1	0.000	0.000	0.000
8:00	21	5.1	0.004	0.000	0.000
9:00	23	6.2	0.022	0.004	0.001
10:00	23	5.7	0.148	0.0547	0.021
11:00	22	5.1	0.424	0.213	0.106
12:00	23	4.6	0.779	0.464	0.270
1:00	23	5.1	1.165	0.792	0.517
2:00	22	5.1	1.600	1.218	0.896
3:00	21	7.2	1.916	1.575	1.256
4:00	20	4.1	2.105	1.810	1.521

Table 5.11 Experimental observations of glass temperatures on Dec. 06, 2009

Time (AM-PM)	***Glass Temperature (°C)***		
	1 cm	**2 cm**	**3 cm**
7:00	16.0	17.0	17.0
8:00	18.6	18.8	18.8
9:00	22.7	21.2	20.6
10:00	28.6	25.0	25.2
11:00	38.5	34.2	30.3
12:00	42.2	38.7	36.2
1:00	43.6	40.8	39.1
2:00	37.3	36.1	35.2
3:00	32.3	33.0	33.0
4:00	29.4	28.2	29.1

Table 5.12 Experimental observations of water temperatures on Dec. 06, 2009

Time (AM-PM)	***Water Temperature (°C)***		
	1 cm	**2 cm**	**3 cm**
7:00	14.0	16.0	16.0
8:00	19.6	19.0	19.1
9:00	27.9	23.5	22.4
10:00	35.1	30.3	28.1
11:00	44.5	39.0	36.2
12:00	46.3	42.5	40.9
1:00	49.4	46.5	44.2
2:00	42.9	41.3	40.3
3:00	38.8	39.7	38.3
4:00	35.6	34.3	34.4

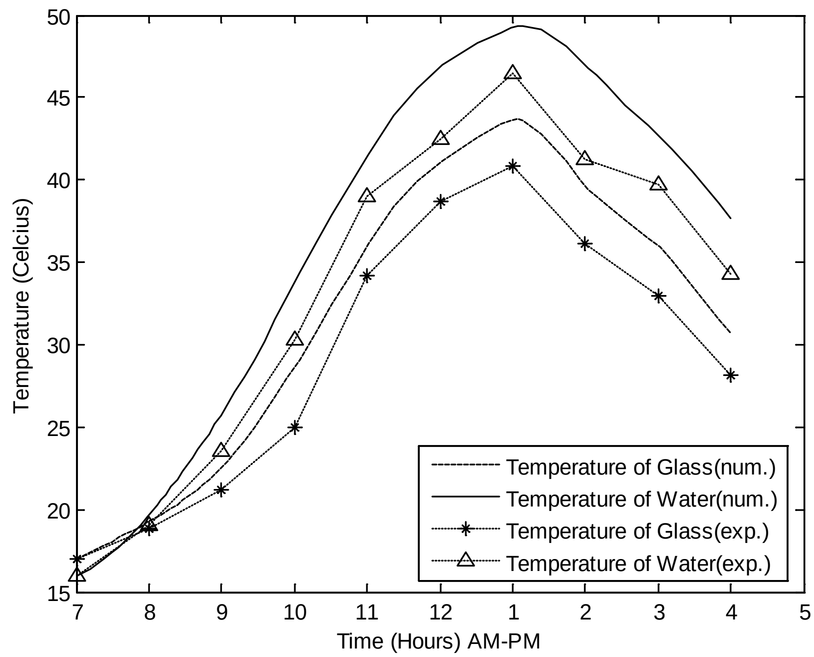

Figure 5.37 Comparison of temperature profiles for 35° slope angle and 2 cm depth

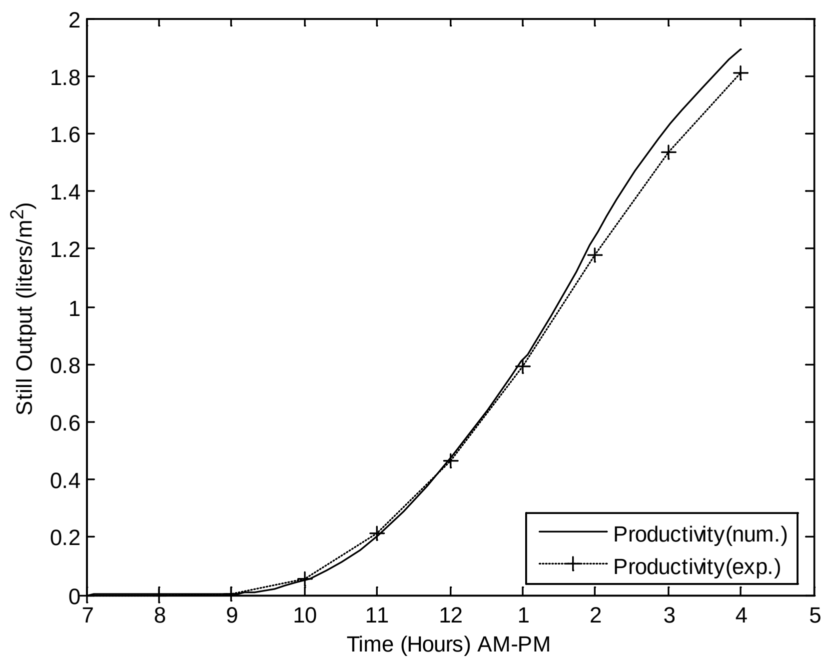

Figure 5.38 Comparison of daily productivity for 35° slope angle and 2 cm depth

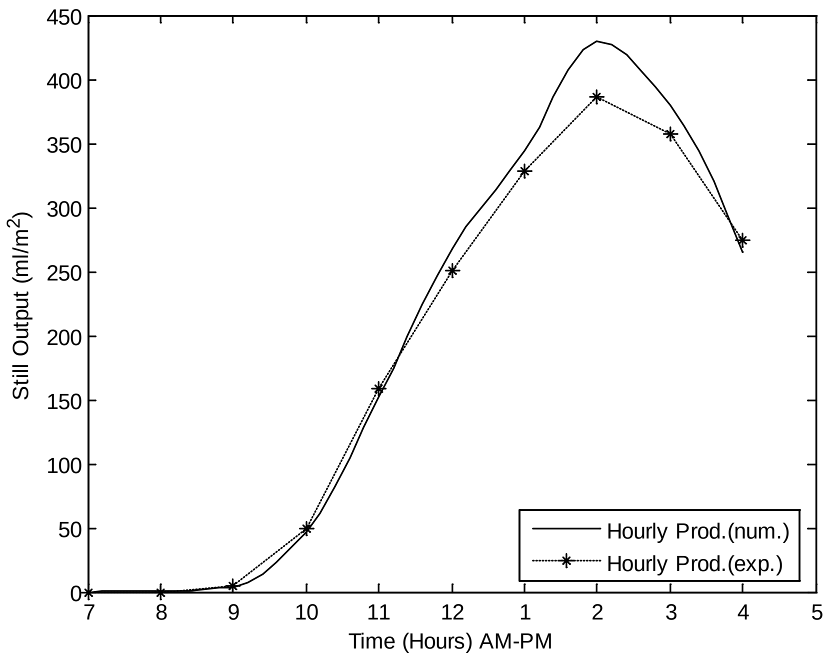

Figure 5.39 Comparison of hourly productivity for 35° slope angle and 2 cm depth

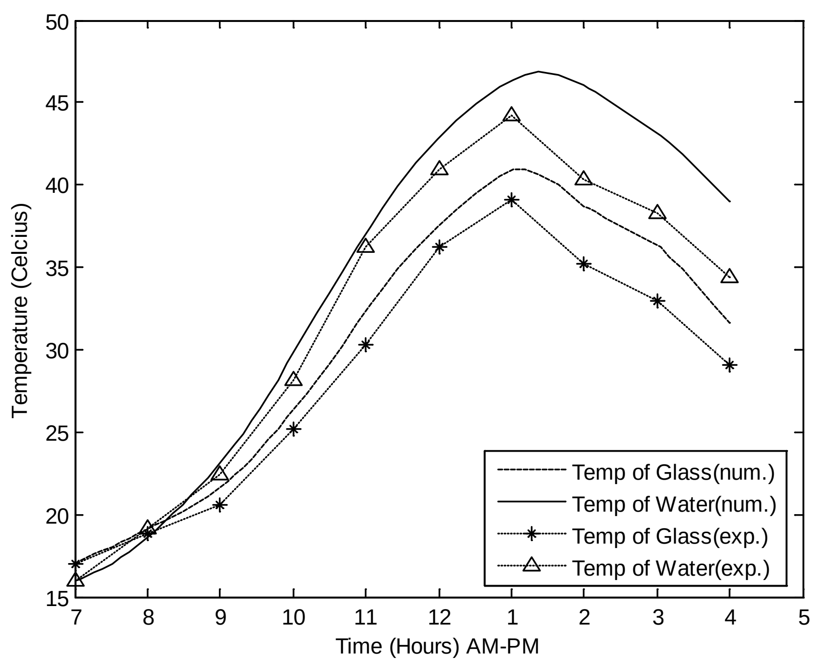

Figure 5.40 Comparison of temperature profiles for 35° slope angle and 3 cm depth

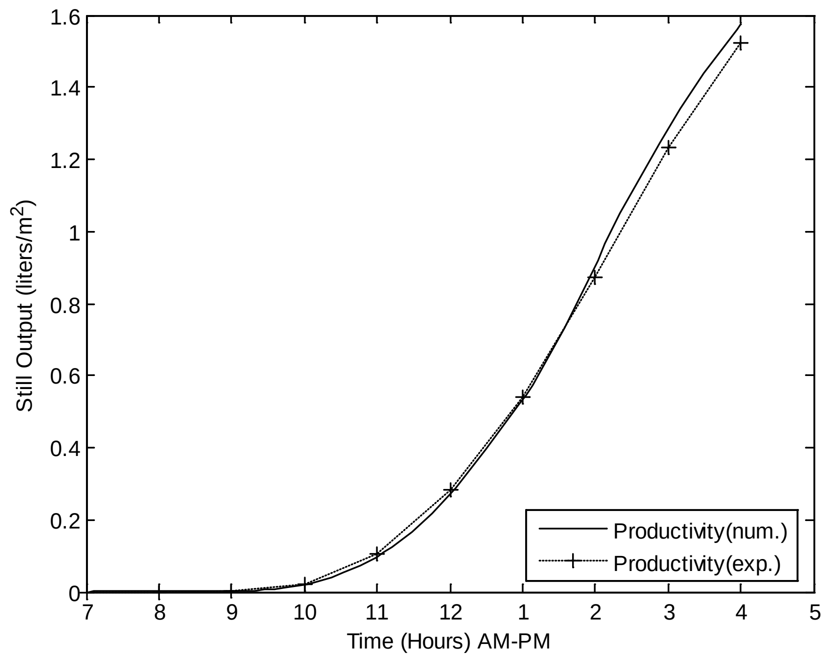

Figure 5.41 Comparison of daily productivity for 35° slope angle and 3 cm depth

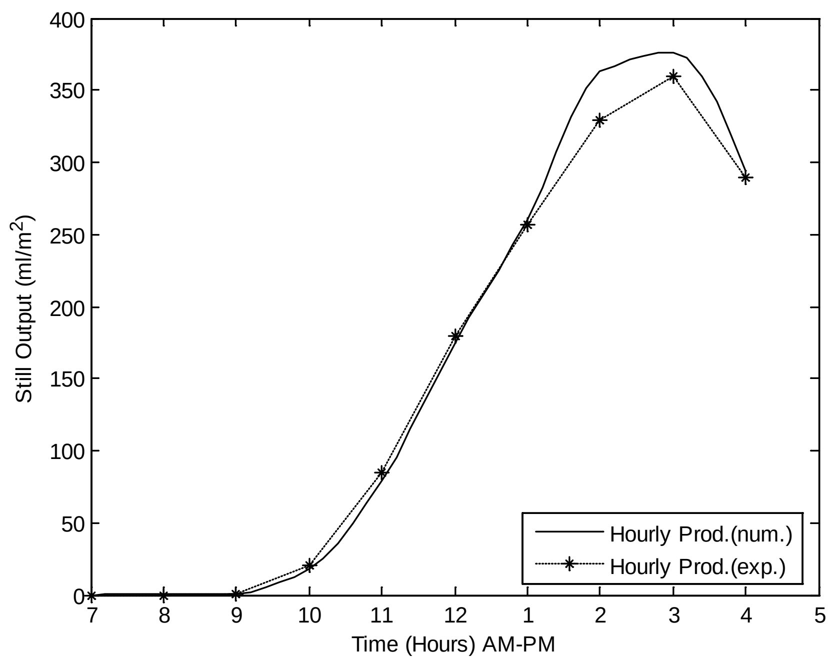

Figure 5.42 Comparison of hourly productivity for 35° slope angle and 3 cm depth

5.2.3 Effect of external mirrors

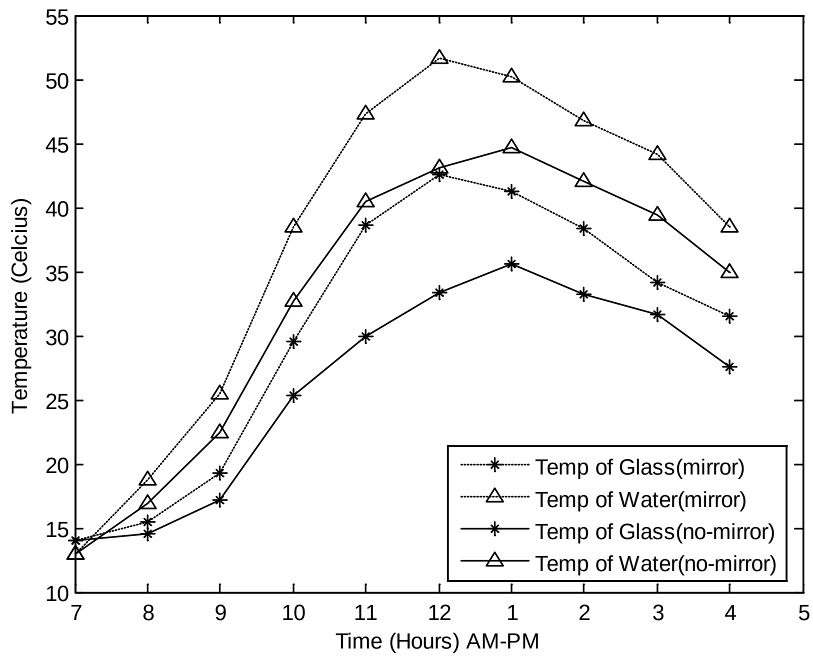

Figure 5.43 Temperature profiles for solar still with and without external mirrors

The experiment was done on 15 December 2009 for which the external mirrors were added to the still. Hourly data for the temperatures and productivity was measured. Fig. 5.43 shows a comparison of temperature profiles for winter season when external mirrors are used to increase the incident radiation on the solar still. It can be seen that a maximum water temperature of 51.6 °C is obtained at 12:00 PM while the peak value of glass temperature is found to be 42.5 °C. The maximum values of water and glass temperatures for the still without the external mirrors were found to be 44.7 °C and 35.6 °C respectively and are attained at 1:00 PM. The external mirrors surrounding the solar still boost the water temperature by reflecting extra radiation onto the still. This boost in water temperature leads to advancement of the peak value of water and glass temperatures by one hour. The fluctuations in the water temperature throughout the day are resulting from the changes in the ambient conditions like solar radiation and wind velocity.

It can be seen that the water temperature increases and reaches a peak value by afternoon because the absorbed solar radiation is more than the heat loss to the atmosphere. Thereafter, the water temperature starts to decrease because the losses from the solar still become higher than the absorbed solar radiation [40].

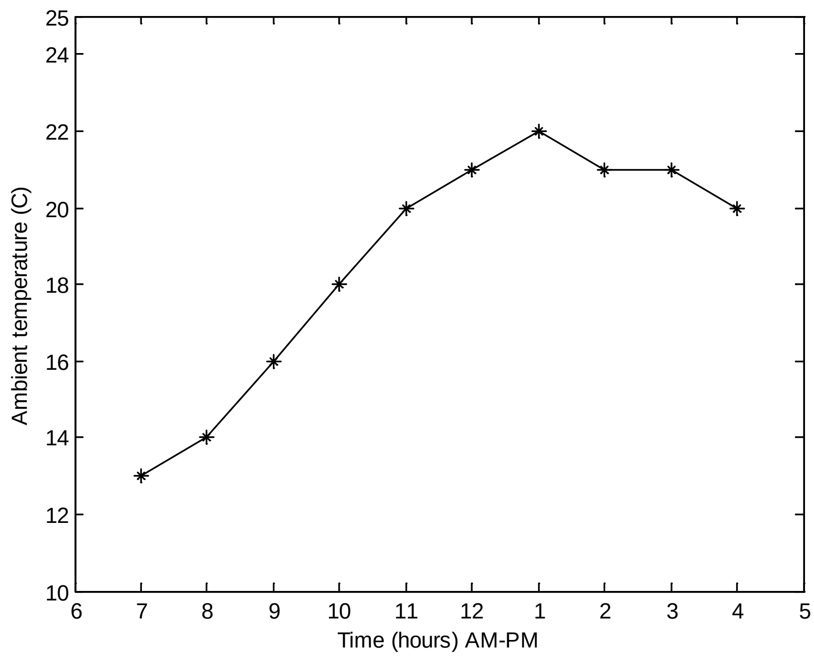

Figure 5.44 Hourly variation of ambient temperature on 15 December 2009

It can also be observed from Fig. 5.43 that the glass temperature increases along with the increase in water temperature. This is due to the heat gained by the glass surface from the evaporated water vapor which condenses on the glass surface. This behavior is quite normal for any solar still. As the solar radiation increases, the heat required for vaporization of water also increases due to which an increase in productivity is observed. The temperature of the water and glass increases because of heat transfer due to convection, radiation and evaporation taking place inside the still.

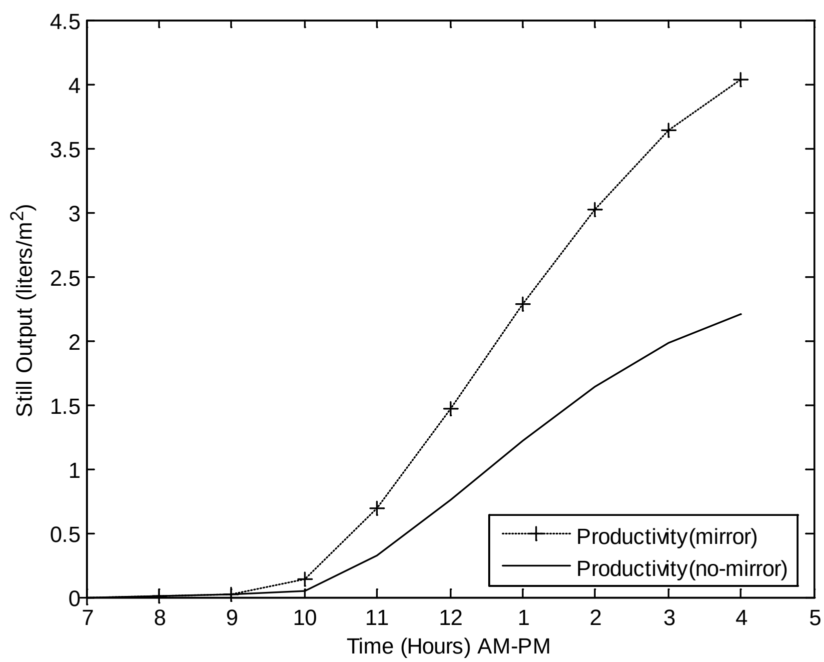

Figure 5.45 Productivity of solar still with and without external mirrors

The hourly variation of distilled water yield is shown in Fig. 5.45. It can be observed that there is a significant increase in the total productivity of the solar still when external mirrors are used around the solar still. The productivity of the solar still with external mirrors is found to be 4.03 l/m^2. Without using external mirrors, the productivity was found to be 2.2 l/m^2. The maximum amount of distilled water was obtained between 12:00 PM and 1:00 PM. The total productivity of the still was found to enhance by a significant 82 %. Thus, the use of external mirrors around the solar still works out very well to enhance the productivity of the still.

The comparison between the experimental and numerical plots for temperature and productivity is shown in Figs 5.46 and 5.47. As seen in these Figs, the experimental and numerical values have the same trend.

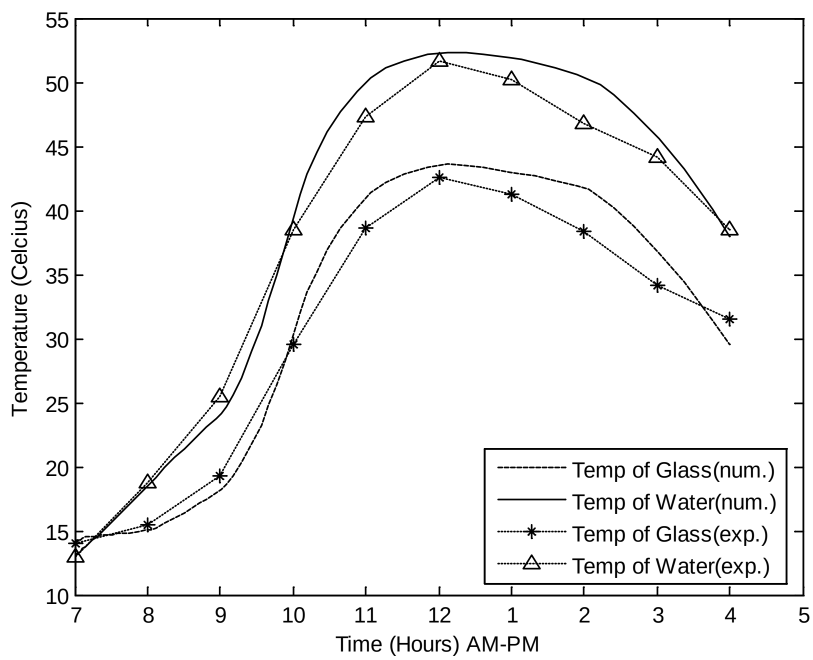

Figure 5.46 Comparison of temperature profiles for solar still with external mirrors

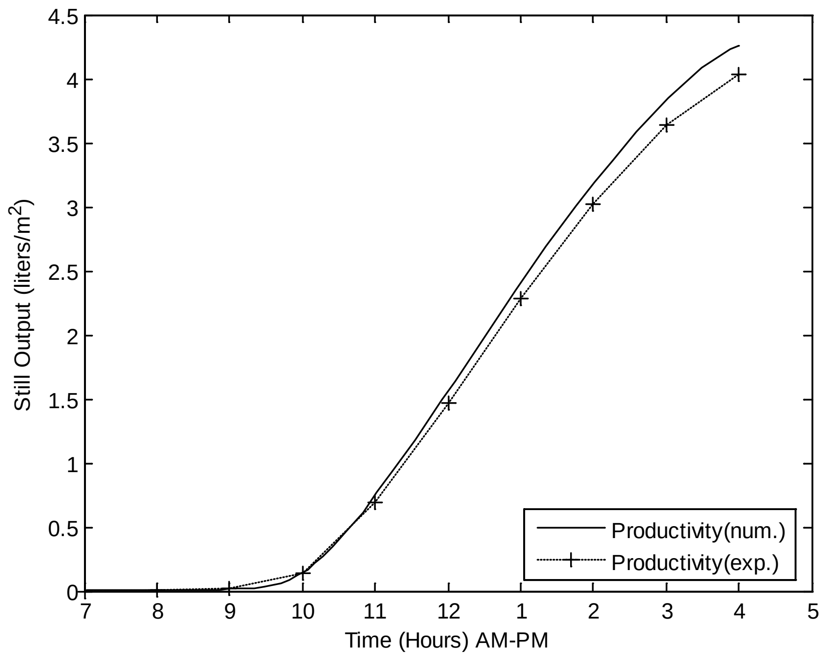

Figure 5.47 Comparison of daily productivity for solar still with external mirrors

Table 5.13 Experimental observations of accumulated productivity on Dec. 15, 2009

Time (AM-PM)	Ambient Temperature (°C)	Wind Speed (m/s)	Accumulated Productivity (liters/m^2) Cover Slope Angle : 35°	
			NO - MIRROR	MIRROR
7:00	14	5.7	0	0
8:00	14	5.7	0.006	0.007
9:00	16	5.1	0.019	0.02
10:00	18	5.1	0.052	0.135
11:00	20	5.1	0.327	0.691
12:00	21	5.1	0.762	1.472
1:00	22	5.7	1.214	2.287
2:00	22	5.1	1.637	3.021
3:00	21	5.1	1.978	3.641
4:00	21	5.1	2.198	4.033

Table 5.14 Experimental observations of glass & water temperatures on Dec. 15, 2009

Time (AM-PM)	(NO- MIRROR) Glass Temperature (°C)	(NO- MIRROR) Water Temperature (°C)	(MIRROR) Glass Temperature (°C)	(MIRROR) Water Temperature (°C)
7:00	14	13	14	13
8:00	14.5	16.9	15.5	18.7
9:00	17.2	22.5	19.3	25.4
10:00	25.3	32.7	29.5	38.5
11:00	30	40.5	38.6	47.3
12:00	33.4	43.1	42.5	51.6
1:00	35.6	44.7	41.2	50.2
2:00	33.2	42.1	38.4	46.8
3:00	31.6	39.4	34.1	44.1
4:00	27.6	35	31.5	38.5

CHAPTER 6

CONCLUSION

The following conclusions can be made based on the results presented in this work.

1. The best glass cover tilt angle for best performance of double slope solar still operating in Eastern Saudi Arabian climatic conditions is 35° for both summer and winter seasons.

2. The best water depth for highest productivity in summer and winter is 1 cm. Water depths below 1 cm are not recommended as a lot of brine accumulation in base tank is expected based on the experimental observations from this study.

3. The highest experimental productivity obtained without mirrors on a typical day for summer and winter is 4.64 l/m^2 and 2.20 l/m^2 respectively.

4. The use of external reflectors increases the productivity of a solar still significantly. In winter, it is found that the productivity increases by 82% when four external mirrors are used.
5. The difference between the experimental and numerical results could be because of vapor leakage from the solar still and the approximations made in the numerical model.

6. Based on the assumptions made in this study, the numerical model is found to predict the experimental results with a tolerable error of 5-10%. Hence, the model

can be used as a reference to simulate the results for different climatic conditions and design parameters.

Solar distillation systems do not consist of any moving parts and can be built from basic raw materials like wood, metal and glass. It provides a technically feasible method for supplying pure water for a small community. This process enables small communities to help themselves so as to improve their standard of living and economic well being. Hence, improvements are continuously being made to increase the productivity of solar still. With further advancement in technology, the use of solar distillation will become more feasible. From the present work, a conference paper [41] has been accepted and a journal paper [42] has been submitted.

CHAPTER 7

FUTURE WORK

Some suggestion for better utilization of the developed model and experimental setup include:

- Changing the material of the base tank and the top cover of the solar still.
- Different insulation materials can be used and their effect on the productivity can be analyzed.
- The effect of providing fins in the base tank of the solar still can be studied.
- Various design modifications can be made to study their effects on the performance of solar still.
- The effect of using energy storage materials in the base tank of the still can be also be studied.
- The use of sponge cubes in the base tank can also be investigated since a significant increase in productivity is reported in literature with the use of sponge cubes.

APPENDIX

Values of constants used in our calculations.

A_b = 1 (m^2)

A_g = 1.22 (m^2)

A_m = 1 (m^2)

C_b = 486 (J/kgK)

$C_{g\,=}$ 840 (J/kgK)

C_w = 4178 (J/kgK)

cc = 1 (m)

K_g = 0.86 (W/mK)

L_{gw} = 1 (m)

m_b = 30 (kg)

rr = 0.61 (m)

S_g = 3.73

S_d = 1.78 (m)

$\rho_w = 1000\ (\frac{kg}{m^3})$

$\tau_S = 0.835$

$\tau_N = 0.835$

$\alpha_b = 0.9$

$\alpha_{gS} = 0.127$

$\alpha_{gN} = 0.127$

$\alpha_w = 0.69$

$\rho_{gr} = 0.5$

$\rho_{ext} = 0.85$

$\gamma = 0°$ (still is due south)

$\epsilon_g = 0.9$

$\epsilon_{wg} = 0.9$

$\rho_m = 0.7$

$\psi = 65°$

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